

2004

# User Authentication and Supervision in Networked Systems

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<http://hdl.handle.net/10026.1/2059>

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<http://dx.doi.org/10.24382/4609>

University of Plymouth

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# **User Authentication and Supervision in Networked Systems**

by

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*B.Sc. (Hons), PGCE*

A thesis submitted to the University of Plymouth  
in partial fulfilment for the degree of

**DOCTOR OF PHILOSOPHY**

School of Computing, Communications and Electronics

Faculty of Technology

**March 2004**

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# **User Authentication and Supervision in Networked Systems**

**Paul Steven Dowland**

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This thesis considers the problem of user authentication and supervision in networked systems. The issue of user authentication is one of on-going concern in modern IT systems with the increased use of computer systems to store and provide access to sensitive information resources. While the traditional username/password login combination can be used to protect access to resources (when used appropriately), users often compromise the security that these methods can provide. While alternative (and often more secure) systems are available, these alternatives usually require expensive hardware to be purchased and integrated into IT systems. Even if alternatives are available (and financially viable), they frequently require users to authenticate in an intrusive manner (e.g. forcing a user to use a biometric technique relying on fingerprint recognition). Assuming an acceptable form of authentication is available, this still does not address the problem of on-going confidence in the users' identity – i.e. once the user has logged in at the beginning of a session, there is usually no further confirmation of the users' identity until they logout or lock the session in which they are operating. Hence there is a significant requirement to not only improve login authentication but to also introduce the concept of continuous user supervision.

Before attempting to implement a solution to the problems outlined above, a range of currently available user authentication methods are identified and evaluated. This is followed by a survey conducted to evaluate user attitudes and opinions relating to login and continuous authentication. The results reinforce perceptions regarding the weaknesses of the traditional username/password combination, and suggest that alternative techniques can be acceptable. This provides justification for the work described in the latter part of the thesis.

A number of small-scale trials are conducted to investigate alternative authentication techniques, using ImagePIN's and associative/cognitive questions. While these techniques are of an intrusive nature, they offer potential improvements as either initial login authentication methods or, as a challenge during a session to confirm the identity of the logged-in user.

A potential solution to the problem of continuous user authentication is presented through the design and implementation of a system to monitor user activity throughout a logged-in session. The effectiveness of this system is evaluated through a series of trials investigating the use of keystroke analysis using digraph, trigraph and keyword-based metrics (with the latter two methods representing novel approaches to the analysis of keystroke data). The initial trials demonstrate the viability of these techniques, whereas later trials are used to demonstrate the potential for a composite approach. The final trial described in this thesis was conducted over a three-month period with 35 trial participants and resulted in over five million samples. Due to the scope, duration, and the volume of data collected, this trial provides a significant contribution to the domain, with the use of a composite analysis method representing entirely new work. The results of these trials show that the technique of keystroke analysis is one that can be effective for the majority of users. Finally, a prototype composite authentication and response system is presented, which demonstrates how transparent, non-intrusive, continuous user authentication can be achieved.



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## **Glossary of Abbreviations**

|              |                                                                                                                                                                                 |
|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>API</b>   | Application Programming Interface – a series of programming interfaces (functions) that provide access to the underlying operating system for an application.                   |
| <b>C-I-A</b> | Confidentiality, Integrity and Availability – the three core measures of system security. Commonly referred to as the CIA of security.                                          |
| <b>CSI</b>   | Computer Security Institute – a US organisation who, together with the FBI, conduct the Computer Crime and Security Survey.                                                     |
| <b>DNS</b>   | Domain Name System – a distributed system storing information to allow the association of string domain names with numeric IP addresses.                                        |
| <b>DTI</b>   | Department of Trade and Industry – a UK government agency set up to assist trade and industry within the UK.                                                                    |
| <b>EER</b>   | Equal Error Rate – a metric used to evaluate authentication products. The EER rate is the point at which both FAR and FRR are equal.                                            |
| <b>FAR</b>   | False Acceptance Rate – a metric used to evaluate authentication products. The FAR rate indicates the proportion of impostors who would be falsely authenticated by the system. |

|       |                                                                                                                                                                     |
|-------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| FBI   | Federal Bureau of Investigation – a US agency set up to defend against terrorism, espionage and to enforce criminal law.                                            |
| FRR   | False Rejection Rate – a metric used to evaluate authentication products. The FRR rate indicates the proportion of valid users who would be rejected by the system. |
| HMSO  | Her Majesty's Stationary Office – a UK government agency responsible for the supply of government information to the public and other interested parties.           |
| ITSEC | Information Technology Security Evaluation Criteria – security assessment criteria developed in Europe.                                                             |
| KPMG  | Klynveld Peat Marwick Goerdeler – a world-wide accountancy firm who conduct regular surveys covering the security issues of medium-large organisations.             |
| RSA   | RSA Security Inc – a worldwide organisation specialising in IT security solutions                                                                                   |
| SMTP  | Simple Mail Transport Protocol – the protocol standard for email transmission across the Internet.                                                                  |

## **Acknowledgements**

I would like to acknowledge the contributions of the following people:

- Dr Steven Furnell, my Director of Studies, for his continued support throughout the research programme, guidance in my research direction and his remarkable inability to fix even the most basic of IT related problems that caused no end of amusement for the research group. Steve provided inspiration and guidance throughout this project, without which I would not have completed this thesis.
- Professor Paul Reynolds, my supervisor, who provided advice and guidance throughout the project. I would also like to thank Paul for securing much needed funding from Orange through a number of research projects.

I would also like to thank specific members of the Network Research Group, namely Nathan Clarke and Harjit Singh for their support.

In addition to those who directly supported the research programme, I would like to thank the survey participants who contributed to the investigation presented in chapter 3. I would also like to thank all the trial participants who assisted in the collection of the keystroke data used in chapters 6, 7 and 8; without whom it would not have been possible to evaluate the techniques implemented. In particular, I would like to acknowledge the

assistance of the staff and researchers of the Network Research Group, the Department of Psychology and the staff of TMA Global and John Nicholls Builders Limited.

I would also like to thank and acknowledge my friends and family for their continued support over the last few years. In particular, to my parents for their encouragement throughout the research programme. Their support has ensured that I continued with my academic career from my first days at school through to the submission of this thesis.

Finally, I would like to thank my fiancée, Simone, who has provided encouragement and endless cups of tea during the final year of the research programme. Her continued support during the write-up stage of the PhD has ensured that this thesis was submitted on time. The final two months of the research programme have been a busy, stressful time for us both and, as such, she has been a tower of strength for me. It is not possible to express in words my appreciation. Thank you.

## **Declaration**

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

Relevant conferences were regularly attended (at which work was frequently presented).

Details of publications (conference and journal) can be found in the appendices.

Signed: ..... *Paul Doulton* .....

Date: ..... 11 / 06 / 04 .....



# **Chapter 1**

## ***Introduction and Overview***

## **1.1 Introduction**

The last two decades have witnessed the use of computer technologies in a wide range of business and domestic scenarios. As such, there are few people in Western society whose lives are not affected by the use of Information Technology (IT). More recently, the explosive growth of both the Internet and the World Wide Web (WWW) has meant that IT has had yet further impacts upon our everyday lives. However, with society's widespread use of and, in some cases, reliance upon technology, significant opportunities now exist for both mischievous and malicious abuse via IT systems. While it is difficult, if not impossible, to prevent all forms of IT misuse, there are a number of methods of addressing the variety of risks that modern computer systems face. One of the key problems in IT misuse is authenticating the identity of end-users in order to both prove the identity of a valid user as well as identifying impostor activity and illicit use of computer resources.

In typical IT systems, protection against unauthorised user activities is usually provided via login authentication. Unfortunately, the majority of authentication schemes are based upon traditional password methods. The weaknesses of passwords are well-known (Jobusch and Oldehoeft, 1989), but their simplicity (from both user and developer perspectives) serves to ensure their continued use. A significant issue with passwords is that they typically provide a one-off authentication judgement at the beginning of a user session. Basing security measures on the identification of the user at the start of the session may prove unsatisfactory, as a user with lower user privileges or an outsider may gain access to the session and masquerade as the original, authenticated and, hence, authorised, user. The normal means of monitoring and identifying this is via audit trails, which maintain a record

of nominated security-relevant activities within the system and can be inspected at a later time in order to identify anomalies. The problem with this approach is that any detection of unauthorised activity will be retrospective, when significant damage may already have been done. If audit trails are not monitored, security breaches may potentially remain unnoticed for some time. What is, therefore, required is an automated, proactive means of detecting and responding to unauthorised access/activity. The research described in this thesis attempts to address a number of these issues.

## **1.2 Aims and objectives of the research**

The objectives of this research programme can be categorised into two parts. Firstly, the range of methods for user authentication were identified and evaluated in order to determine currently available techniques and consider alternatives. This informed the second objective; namely the design of new methods and the development of associated practical experiments conducted to evaluate the alternative techniques, as well as considering user attitudes and opinions following exposure to the methods under trial.

The thesis begins by analysing the current methods of user authentication as well as considering the concept of user supervision. The user preference for secret-based authentication techniques is considered, together with the inherent weaknesses that these approaches present. User behaviour is considered by looking at the use (and misuse) of current authentication techniques, before a survey was conducted to determine the attitudes and perceptions of computer users to existing authentication techniques as well as introducing alternative methods.

The research continued by considering the practical implementation of a number of alternative user authentication mechanisms. In implementing these alternative approaches a key aim was to improve the level of security without causing the user to perform explicit actions (e.g. to provide authentication details) or to have to modify software (or their own behaviour). While the earlier trials considered improvements in the initial login authentication utilising secret-based methods, in order to achieve these objectives the later trials developed into transparent, continuous, real-time user supervision. The practical implementation of these techniques is evaluated via a series of prototype implementations.

The objectives for the research programme can be summarised as follows:

1. to investigate the current methods of user authentication/supervision within computer systems;
2. to assess user attitudes towards current authentication systems, as well as the acceptability of alternative authentication approaches and the concept of continuous user supervision;
3. to design new methods for improving user authentication and continuous user monitoring;
4. to evaluate the methods implemented and produce recommendations on necessary improvements;

5. to examine how the techniques can be applied in a wider, more comprehensive security system;
6. to recommend future development and propose further work relating to the research programme.

The objectives outlined above relate to the sequence of material presented in the following chapters in the thesis, the outline structure for which is presented in the next section.

### 1.3 Thesis Structure

This thesis presents the outcome of research conducted to investigate and evaluate alternative user authentication and supervision techniques in a modern PC environment. The thesis begins by considering the general area of user authentication before identifying potential approaches for further investigation. The chosen techniques are then evaluated in detail, and experiments conducted to evaluate the effectiveness of the approaches.

Chapter 2 presents a general overview of current issues relating to computer security and draws upon a number of examples of recent incidents to demonstrate the risks faced by computer systems. This is followed by a summary of the classifications of those responsible for computer abuse incidents in order to gain a better understanding of the different types of offenders. Having considered the background to computer abuse, the chapter then focuses upon the limitations of current user authentication techniques, considering the classic classifications of what the user *knows*, *has* and *is*. The chapter then

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proceeds to discuss the problems with the current preferred technique, namely the password, before considering the alternatives. A significant section of the chapter is then dedicated to the consideration of a range of biometric based techniques, and finally summarising the relative merits.

Having evaluated a range of alternatives to the simple password, chapter 3 presents the results of a survey evaluating user attitudes and perceptions regarding a range of authentication techniques. This survey evaluated a range of issues in order to determine the acceptability of alternative techniques to the end users. The chapter begins by summarising current password practices (from a user perspective), before presenting the participants with a range of alternatives. The results of this survey informed the selection of techniques for further evaluation.

Following the selection of a subset of potential approaches, chapter 4 presents the results of two trials conducted to evaluate a range of secret-based authentication techniques. As these techniques are popular among users, this chapter focuses on methods that utilise secret knowledge. The chapter begins by presenting the technical implementation followed by the results of two trials aimed at evaluating both user recall of secret information and the long-term perceptions of user-friendliness and acceptability of these approaches.

Chapter 5 progresses beyond the use of secret-based techniques to present an overview of the concept of keystroke analysis. This chapter begins with a discussion of the range of metrics that can be obtained through keystroke analysis, and the ways in which these can be interpreted. Following this, the chapter identifies a range of ways to obtain the

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identified metrics under the Windows operating system together with discussion of the potential integration of keystroke analysis directly into the Windows security model. The discussion then moves on to consider the role of filtering and post processing before summarising previous work in the area. Finally, the chapter identifies a series of new approaches to keystroke analysis, considering the use of trigraph, keyword and application-specific profiling.

Chapter 6 takes the proposed techniques from chapter 5 and describes an experimental implementation of keystroke dynamics aimed at evaluating the methods previously identified. The chapter begins with a detailed description of the software developed for the experiment and the features of the underlying operating system that were utilised. This is followed by a discussion of the analysis of the data, before considering the results of the trial. The chapter concludes with a brief discussion of a novel use of data mining for keystroke analysis, before presenting an initial experiment of the use of an application-specific approach.

Following the small experiment described in chapter 6, chapter 7 presents the results of a long-term experiment evaluating digraph, trigraph and keyword-based keystroke analysis. The chapter begins by presenting the technical implementation of the keylogging software and utility programs used to filter the raw data, generate the profiles and compare the samples. Following this, the chapter presents the results for each of the separate metrics.

Chapter 8 extends the work presented in chapter 7, and considers alternative approaches and concepts. This chapter presents the results of a composite approach that combines the three metrics evaluated in the previous chapter, before introducing a composite

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authentication and response system based upon the software described in chapters 4, 6, 7 and 8. This is presented as a prototype implementation to demonstrate the effectiveness of these techniques in an operational context.

Finally, chapter 9 presents the conclusions drawn from the research conducted and presented in the thesis. The key achievements are emphasised, together with the limitations on the research programme. This chapter also suggests a number of potential extensions to the research described in the earlier chapters, and identifies a number of possible improvements to the experiments conducted.

The thesis also includes a number of appendices containing additional information to support the discussion presented in the main chapters. In addition a CD is provided that includes source code from the experiments described in chapters 6, 7 and 8, as well as the raw results (too large to include in the body of the thesis). Finally, a number of published papers arising from the project are included, as well as a list of papers produced during the same period that are less directly related to the PhD research.



## **Chapter 2**

### ***Evaluation of Current Authentication Measures***

## **2.1 Introduction**

The last two decades have witnessed the integration of personal computer technologies into a wide range of business and domestic scenarios. As such, there are few people in Western society whose lives are not affected in some way by the use of IT. More recently, the growth of the Internet and the WWW has meant that IT has had yet further impacts upon our everyday lives. This is set to increase over the coming years with the increased availability of new technologies – especially with an increasingly mobile and technically minded public. However, with society's widespread use of, and, in some cases reliance upon, technology, significant opportunities now exist for both mischievous and malicious abuse of IT systems.

Over the past 20 years, the UK Audit Commission has conducted a series of surveys to assess the scale of crime and abuse within the IT community. The results of these surveys show a significant upward trend in overall crime levels during this period (Table 2.1). The audit commission surveys are not alone in these findings with surveys conducted by the CSI in the USA showing similar rises in computer crime (CSI, 2003).

It should be noted that the categorisation of various types of computer crime cases has varied slightly over the twenty years of the Audit Commission surveys. In particular, the category of 'viruses' was not included until 1990 and cases of offences involving pornographic material were not reported until 2001 (the latest survey results currently available). In the 1984-1990 surveys the definition of the category "theft" was quite broad and covered the use of unlicensed/illicit software, private work and theft (of equipment or

data) while the category “hacking” covered hacking, sabotage and invasion of privacy. For the comparisons of later surveys, these categories have been maintained for consistency.

|      | Fraud | Viruses | Theft | Hacking | Pornography | Other | Total |
|------|-------|---------|-------|---------|-------------|-------|-------|
| 1984 | 60    | -       | 17    | -       | -           | -     | 77    |
| 1987 | 61    | -       | 22    | 35      | -           | -     | 118   |
| 1990 | 73    | 54      | 27    | 26      | -           | -     | 180   |
| 1994 | 108   | 261     | 121   | 47      | -           | -     | 537   |
| 1998 | 67    | 247     | 88    | 56      | -           | 52    | 510   |
| 2001 | 50    | 200     | 19    | 44      | 193         | 119   | 625   |

Source: UK Audit Commission 1984-2001

**Table 2.1 - Reported incidents of computer crime and abuse**

It is clear that over the last 20 years there has been a significant increase in the number of reported incidents. A clear factor influencing this increase is the explosion in virus incidents that can be observed from the 1990s and the subsequent increase in cases relating to the access or distribution of pornographic materials in the most recent survey. It is worth noting that, in the latest results, ‘pornography’, ‘use of unlicensed software’ and ‘private use of company IT resources’ are the only categories of abuse in which the reported incidents have risen (in both real terms and as a percentage of incidents reported) when compared to the previous surveys (193 cases relating to pornographic material, 35 cases relating to unlicensed software and 72 cases relating to private use of company resources).

These findings are echoed in the surveys conducted in the USA by the CSI/FBI through their computer crime and security surveys. The most recent report (CSI, 2003) showed 56% of organisations suffering from unauthorised use of corporate computer systems (slightly down on the 60% reported in the previous year). Of the 490 organisations

surveyed, 45% reported unauthorised access to computer resources by insiders and 80% reporting insider abuse of network access. This shows a high level of computer misuse appearing from inside an organisation – misuse which may be prevented by improved user authentication and/or monitoring of user actions.

Over the last few years there have been numerous incidents that have been reported in the media that have reaffirmed the susceptibility of IT systems to abuse. Examples of these incidents include the MyDoom virus (and its variants) and the mass defacement challenge (a number of recent incidents are outlined in Table 2.2).

| Incident        | Details                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| MyDoom worm     | January 2004<br>Mass mailing and peer-peer file-sharing worm <ul style="list-style-type: none"><li>• contained an SMTP server to send emails (spam/replication)</li><li>• contained a backdoor to allow IP spoofing or remote code execution</li><li>• contained a Denial of Service payload targeting the SCO (and Microsoft in the MyDoom.B variant) web sites</li></ul> At the peak of the infection it was estimated that 20-30% of all worldwide email traffic was generated by MyDoom.<br>(F-Secure, 2004) |
| Mass defacement | July 2003<br>Global hacking competition conducted to deface web sites.<br>Target of 6,000 web sites hacked in 24 hours<br>There is no confirmed count of defacements but the figures are estimated to be in the region of a few thousand.<br>(ZoneH, 2003)                                                                                                                                                                                                                                                       |
| Global DDoS     | June 2003<br>Global distributed denial of service (DDoS) attack.<br>The web sites of Clickbank and Spamcop were victims of a global DDoS attack suffering over 1000 hits per second.<br>(Schultz, 2003a)                                                                                                                                                                                                                                                                                                         |

Table 2.2 - Example IT security incidents

Before we can look at ways of improving IT security, it is first necessary to understand the issues that affect computer systems. There are four main issues relating to computer

security (ITSEC, 1991) and overall IT system security relies on the preservation of all of these factors.

- Confidentiality

The term confidential is indicative of a level of secrecy and is clearly understood. This generally refers to the prevention of unauthorised disclosure of information and has a familiar comparison with a “need to know”, military-style, security model. The consequences of a breach of confidentiality are usually dependent on the context of the breach. From an organisational perspective, if confidential content is accessible to a third party the consequences are probably more significant than if someone inside the organisation accessed the same material.

- Integrity

Integrity of data can be more difficult to analogise, as it relates to the consistency, completeness and correctness of data. An impostor or masquerador could potentially make minor changes to data files or programs (e.g. to siphon off small amounts of money *lost* in account transactions through rounding errors) that would not necessarily be identified immediately. Not all breaches of data integrity are malicious, however, even accidental modification/deletion of data can cause serious problems (e.g. a user mistakenly deleting an important file). Viruses represent one of the commonest threats to IT system integrity with payloads that can modify/delete files.

- Availability

With an increased dependence on IT systems, their availability (or uptime), is increasingly important. Users expect systems to be available whenever and wherever they need them. While this used to concentrate on defence against mechanical/logical failure, it is now equally (if not more) important to consider the threat from malicious activity which can render a system inaccessible. Known as a Denial of Service (DoS), this form of malicious activity was used to significant effect against several major Internet sites (Yahoo, Amazon and eBay to name a few) in the worldwide attacks in early February 2000, effectively holding systems hostage (McCullagh and Arent, 2000). A recent survey (CSI, 2003) identified DoS attacks as the second most expensive form of incident affecting respondent organisations and costing industry in excess of \$65m.

- Accountability

Whilst not usually considered a part of the C-I-A trio, accountability is vitally important to allow actions and intrusions to be tracked. Without some form of accountability it is impossible to directly attribute an action to an individual or to be able to prove that an individual did *not* perform a specific action (i.e. through authentication we should be able to hold an individual accountable for their actions or, alternatively to be able to defend an individual or organisation). Accountability is usually achieved through historical logs, however this only allows action to be taken after the event, therefore some form of interactive monitoring is needed to audit (and respond to) user actions

in real-time. Action in response to illegitimate activity needs to be taken proactively rather than reactively.

## 2.2 Categorising system intrusions and misuse

Whilst the previous section discussed the four specific issues relating to IT security, it is also necessary to understand the sources from which computer abuse is likely to be encountered. This is important, as although it is necessary to appreciate the differing forms of computer abuse, it is also important to consider the nature of the person undertaking the misuse. By examining the perpetrators of computer crimes, it may be possible to evaluate the motives and hence to reduce the risks faced by IT systems. Forms of human abuse have already been comprehensively categorised by Anderson (1980), and are described in Table 2.3.

| Abuser Type          | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| External Penetrators | Outsiders attempting or gaining unauthorised access to the system.<br>E.g. a hacker trying to download the password file(s) from a server or a rival company trying to access the sales database.                                                                                                                                                                                                                                                                                                                                                 |
| Internal Penetrators | <p>Authorised users of the system who access data, resources or programs to which they are not entitled. Sub-categorised into:</p> <ul style="list-style-type: none"> <li>• <i>Masqueraders</i> Users who operate under the identity of another user.<br/>E.g. someone using another users' PC whilst they are absent from their terminal, or, someone using another's username/password.</li> <li>• <i>Clandestine users</i> Users who evade access controls and auditing.<br/>E.g. someone disabling security features/auditing etc.</li> </ul> |
| Misfeasors           | Users who are authorised to use the system and resources accessed, but misuse their privileges.<br>E.g. someone in the payroll department accessing a colleague's records or misappropriating funds.                                                                                                                                                                                                                                                                                                                                              |

Table 2.3 - Categories of system abuser

These groupings are considered appropriate for describing the different types of user-related abuse within an intrusion-monitoring framework and will, therefore, be adopted for the remainder of the discussion. Whilst it is also possible to develop a deeper profile of potential intruders, by considering factors such as the common motivations behind abuse (e.g. money, ideology, egotism etc.), these are not explored here as knowledge of them would not contribute to the process of detection. However, this subject was discussed in a paper published in 1999 (Furnell et al) in which the motivations, ethics and perceptions of computer criminals are explored and the role of the media is considered.

It should be noted that Anderson's categorisations do not take into account any of the types of abuse that may result from software activity (e.g. viruses, Trojan Horses etc.). This is understandable given that the analysis was made in 1980 before such incidents had become commonplace. However, there has been a significant increase in such attacks over the last decade and evidence suggests that viruses are one of the major causes of security breaches in both networked and standalone PC systems (CSI, 2003).

### **2.2.1 Internal Penetrators and Misfeasors**

At the highest level, intrusions or misuse will be the result of actions by authorised users or processes, which operate on one or more targets that may include data (files), system devices and other users or processes. It has been shown that the most significant source of computer system abuse is from within the organisation (Dinnie, 1999; ISBS, 2000). Therefore, if we can secure systems against internal abusers, we will be targeting the most likely perpetrator. Unfortunately, internal abusers are quite likely to be authorised to use



the systems they are abusing, hence reliance on the basic username/password will only serve to, retrospectively, attribute blame once the abuse has been detected. In order to detect and prevent abuse in real time, it is necessary to introduce an element of user supervision.

The purpose of introducing supervision will be two-fold:

- to ensure that systems are only accessed by authorised users;
- to ensure that systems are only used for authorised purposes.

By introducing user supervision it is possible to monitor, in real time, the actions of individual users at a variety of levels. Monitoring could take place at operating system level; monitoring key files, directories or resources (e.g. printers and CD writers) or individual applications could be monitored (e.g. a database application could be monitored for export of data or deliberate deletion of data). Alternatively, a higher-level approach could be taken. A supervision application could be loaded into a system that would monitor specific characteristics (akin to a lifeguard watching a swimming pool from a high vantage point). When an uncharacteristic pattern is monitored (e.g. a person panicking in the deep end of the pool) an appropriate response can be initiated. This could potentially identify a user acting in an unusual or unexpected manner (e.g. conducting tasks outside of their defined role) or could identify a user account being used by an impostor.

User actions can be categorised as being either legitimate or illegitimate. However, it is useful if a more detailed breakdown than this can be derived for the different potential

classes of illegitimate activity. For example, all of the following scenarios represent types of illegitimate activity that should be monitored:

- an illegitimate action that is still within the normal authorisation of a valid user (i.e. abuse of privileges);
- an action by a valid user which is outside the normal limits of authorisation;
- any action by an unauthorised user.

### **2.2.2 External Penetrators**

Whilst sources of abuse within the organisation are the most likely form of abuse, they are usually the least damaging to a company and its reputation. The reason for this is that being internal attacks, they are usually dealt with by the company concerned and rarely have any external impact. External penetrators are quite different. Due to the intrusive nature of such attacks, they are more likely to have a visible, external impact. Examples of this could include company blackmail, attacks against web sites and financial loss from e-commerce systems. Although most of these attacks can be described as prank or hoax attacks, they will often have a significantly negative effect as they undermine the company's public image. A particularly apt example of this was the hack of the RSA security web site in February 2000 (2600, 2000). (It should be noted that the server on which the RSA web site was held was not actually hacked. Instead, the perpetrator, a hacker named Coolio, was able to modify the DNS records to redirect traffic destined for the RSA web site to a different server.) The consequence of this particular hack was the rather unfortunate headlines indicating that a company purporting to provide high security

solutions was itself hacked – the media choosing to overlook the nature of the attack that was actually outside the control of RSA.

## 2.3 Limitations of current technology

Having identified and categorised the main sources of computer abuse, this section considers the current methods of protecting IT systems and identifies their shortcomings. There are three main approaches to user authentication, something the user knows, something the user has and something the user is (Wood, 1977). Table 2.4 summarises these 3 main forms of authentication and provides examples as well as indicating the known weaknesses of each method. These methods will all be discussed in more detail in the next section(s).

| Something the user... | knows                                                                                                                                                                  | has                                                                                                                                                               | is                                                                                                                                                                                                                                   |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Example</b>        | <ul style="list-style-type: none"><li>• Password</li><li>• PIN</li><li>• Other secret knowledge (e.g. personal information)</li></ul>                                  | <ul style="list-style-type: none"><li>• Magnetic card</li><li>• Smart card</li><li>• Proximity device (e.g. RF tag)</li></ul>                                     | <ul style="list-style-type: none"><li>• Physiological (e.g. fingerprint, retinal scan)</li><li>• Behaviour e.g. keystroke analysis</li></ul>                                                                                         |
| <b>Weaknesses</b>     | <ul style="list-style-type: none"><li>• Can be guessed</li><li>• Often chosen inappropriately</li><li>• Vulnerable to social engineering or shoulder surfing</li></ul> | <ul style="list-style-type: none"><li>• Can be stolen</li><li>• Potentially replicated</li><li>• Dedicated hardware needed (e.g. magnetic card reader).</li></ul> | <ul style="list-style-type: none"><li>• Usually requires dedicated hardware to profile and authenticate</li><li>• If breached, users cannot replace their identifying characteristic (e.g. cannot grow a new fingerprint).</li></ul> |
| <b>Strengths</b>      | <ul style="list-style-type: none"><li>• Easy to implement</li><li>• Easy for users</li></ul>                                                                           | <ul style="list-style-type: none"><li>• Can be combined with knowledge (e.g. pin plus swipe card)</li></ul>                                                       | <ul style="list-style-type: none"><li>• Depending on measure is highly unique to the individual.</li><li>• Cannot be forgotten by user</li></ul>                                                                                     |

Table 2.4 - Examples of authentication measures

The most commonly used means of authentication in IT systems is the password. Passwords are conceptually simple for designers and users and can provide effective

protection if used correctly. However, their protection is often compromised by users. Typical problems include forgetting passwords, writing them down, telling other people your password and selecting easily guessed passwords.

Several studies have been carried out over the last 30 years looking at the ease with which passwords can be determined. In 1979, 86% of the 3829 passwords gathered, could be guessed by a PC in less than 1 week (Morris & Thompson, 1979). This was repeated in 1990 by Klein and in 1992 by Spafford (Klein, 1990; Spafford, 1992). Whilst the results from these later experiments showed that password selection had improved (only 21% could be guessed in 1 week), so have the tools that can be used to guess passwords. In 1998, L0pht Heavy Industries developed L0phtCrack (Heskett, 1998) - later renamed and re-released as LC4 when bought out by @stake (2004). @Stake is a utility that allows Windows NT Server Message Block (SMB) password packets to be captured during network authentication sessions (although the product is advertised as a password auditing and recovery tool). This utility not only allows the encrypted passwords to be captured directly off the network, it can also perform a dictionary and brute force attack against the encrypted passwords. Similar utilities are also available for other operating systems (notably CRACK which runs under a number of flavours of UNIX) (Cherry et al, 1992). More recently, researchers from the Swiss security organisation Lasec developed "Advanced Instant NT Password Cracker" (Schultz, 2003b). This prototype application (only available as a demo from the web site) claims to be able to crack Windows user account passwords in hours rather than days.

There are a number of measures that can be taken to improve password security for example:

- **Non-Dictionary Words**

Forcing users to select non-dictionary passwords prevents the use of dictionary based attacks. A dictionary attack can identify a password in less than 20 minutes even on word lists with up to one million words. The only way to identify non-dictionary passwords is by using a brute-force approach (testing every combination of characters for every length of password).

- **Passwords with mixed case/symbols**

Including both upper/lower case and symbols (!£\$% etc.) in passwords requires any attack to use a brute force method. The use of these extra characters exponentially increases the time taken to determine the password by increasing the key-space that must be searched through.

| <b>Password Characters</b>                                                                     | <b>4 Character Password</b> | <b>8 Character Password</b>      |
|------------------------------------------------------------------------------------------------|-----------------------------|----------------------------------|
| a-z                                                                                            | 456,976 ( $26^4$ )          | 208,827,064,576 ( $26^8$ )       |
| a-z, A-Z                                                                                       | 7,311,616 ( $52^4$ )        | 53,459,728,531,456 ( $52^8$ )    |
| a-z, A-Z, 0-9                                                                                  | 14,776,336 ( $62^4$ )       | 218,340,105,584,896 ( $62^8$ )   |
| a-z, A-Z, 0-9, and special characters e.g. !, ", £, \$, %, ^, @, # etc. [Approx 82 characters] | 45,212,176 ( $82^4$ )       | 2,044,140,858,654,976 ( $82^8$ ) |

Table 2.5 - Character combinations for passwords

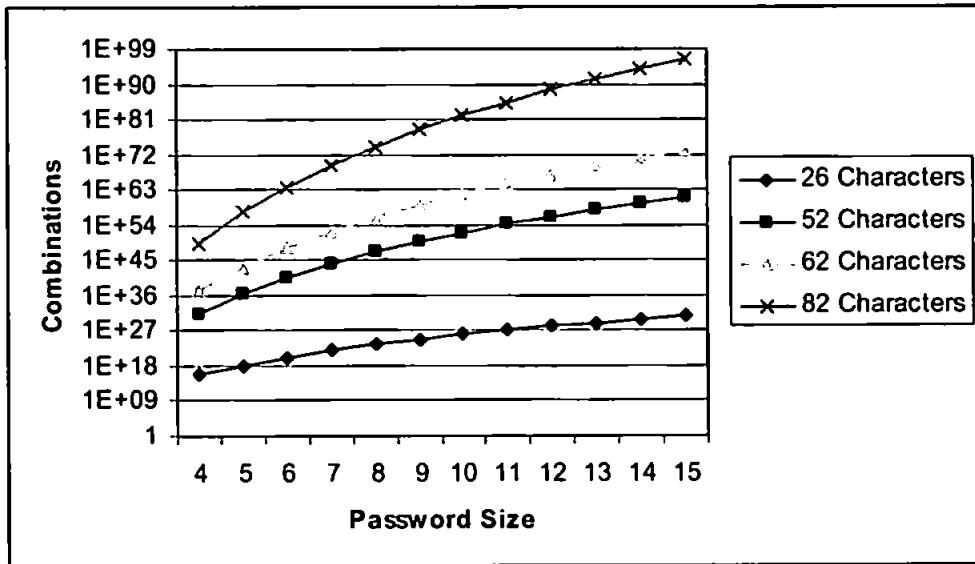


Figure 2.1 - Exponential increase in password complexity

- Password Ageing

Should an intruder obtain a valid username/password combination most systems will allow the intruder to continue to access the system until the intrusion is noticed. If a password ageing policy is in place users can be forced to change their passwords regularly, thus forcing the intruder to identify the new password.

Whilst these suggestions will help to make a password-based system more resilient to an intruder they are by no means secure. A determined intruder can utilise password-cracking utilities to determine even the most random password in a matter of weeks. With the advent of more powerful processors, intruders will be able to crack passwords in a more realistic time – a matter of days for some PCs. A more worrying issue is the failure by some users to protect their own passwords. None of the measures outlined above help to address the human-element of the problem. This was demonstrated in a recent survey conducted at the InfoSec conference at Olympia (IT Week, 2003). The survey revealed

that of the 150 people questioned, more than 100 were prepared to give their passwords to a complete stranger – tested most effectively by simply asking people what their password was. While not very scientific, the survey did highlight a fundamental problem with IT security – we still rely on users! To counter these problems with password based systems, we need to consider alternative approaches to user authentication. Another factor suggesting the use of alternatives is that any of the above means of strengthening passwords ultimately reduce their simplicity and friendliness for users.

## **2.4 Methods of Improving Authentication**

To meet the demand for alternative methods of user identification and authentication, there are a growing number of companies offering both hardware and software based products. Solutions range from basic (and cheap) keystroke analysis software (BioPassword, 2004) to sophisticated iris and retinal scanning devices (Secure Computing, 1995; Sherman, 1992; Cope, 1990). Many of these devices can be incorporated into desktop PC's and can usually be configured into a network-wide security policy. However, most of these products utilise proprietary technology in both the hardware and software making it impossible (or at the very least difficult) to integrate products purchased from a variety of manufacturers. There is also considerable variability in the extent to which the software provided can integrate with the operating system's security model. Some products simply provide an additional layer of security, requiring the user to authenticate themselves in addition to providing a valid username/password pair, whilst others provide replacement logon interfaces and fully integrate into the security model of the OS. However, some work has been done by OS vendors to provide a standardised application programming

interface (API) to allow product vendors to integrate their identification/authentication and monitoring devices/products into the OS security kernel (BioAPI, 2004; Microsoft, 2000).

As indicated earlier in Table 2.4, the three main methods of user authentication have a number of weaknesses. Passwords can be written down, forgotten and shared; tokens or cards can be stolen, copied or lost whereas the alternative, biometrics provides a seemingly near-perfect solution. If the problems of cost, user acceptance and integration can be overcome (not insignificant problems on their own) the use of biometrics could be a solution to the problems of user authentication. Biometric characteristics cannot be (easily) lost, stolen or duplicated; are usually stored in a non-reproducible manner and offer a high level of authentication confidence (depending on the methods chosen).

Methods of biometric-based user authentication fall into two distinct categories, specifically physiological and behavioural characteristics.

- Physiological characteristics represent those traits that describe who we are based on physical attributes, for example fingerprints, hand geometry, retinal and iris scanning. These characteristics usually require additional equipment to be connected externally to the computer to provide the necessary data capture.
- Behavioural characteristics cover attributes such as typing style, voice pattern and signature recognition. Most behavioural characteristics can be acquired without the need for additional equipment (keyboard & mouse)



however others do require specialised hardware solutions (signature recognition).

Most biometric devices offer a compromise between high security/low user acceptance and low security/high user acceptance. This trade-off can be measured as the False Acceptance Rate (FAR) and False Rejection Rate (FRR) of the devices. Figure 2.2 shows the relationship between the FAR and FRR rates and can be seen to be mutually exclusive.

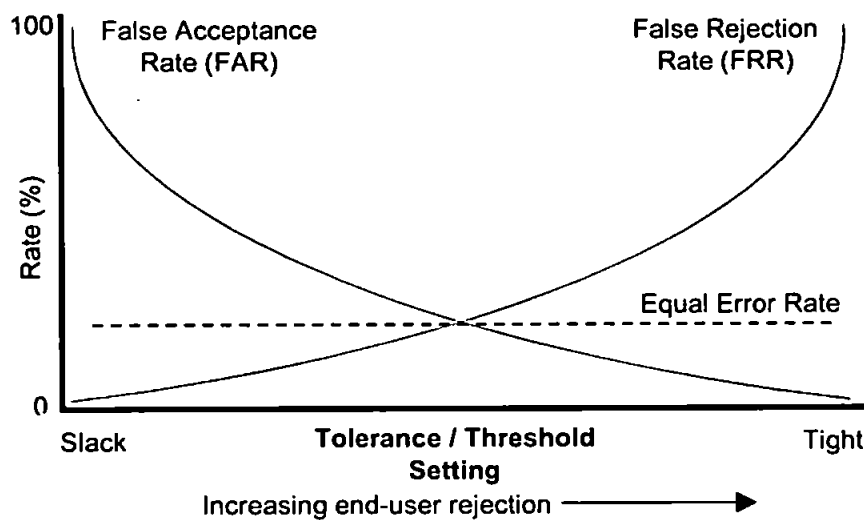


Figure 2.2 - FAR/FRR Graph

FAR represents the proportion of invalid users who will be successfully authenticated by a system (i.e. falsely accepting an unauthorised user). FRR represents the proportion of valid users who will be identified as illegitimate by the system (i.e. incorrectly rejecting an authorised user). The error rates of an authentication system are assessed using a fixed population of test users and usually involves cross testing of users against the profiles of all other users in the trial. This allows consistent testing of error rates, but results in rates based on a subset of the population – i.e. it does not consider a true intruder (an individual unknown to the system). Despite this flaw, the use of FAR/FRR rates is widely used as a

metric for authentication techniques and, as such, is used within this thesis to allow appropriate comparisons to be made to existing techniques. It has so far proved impossible to achieve a system where the FAR and FRR rates have both been reduced to 0. Most systems, instead, select an appropriate level at which inconvenience to the legitimate user, through denial of access (rejected logins), is acceptable, without allowing too many intruders to gain unauthorised access. All systems have an Equal Error Rate (EER), the point at which the FAR and FRR rates are equal. Whilst this rate represents the theoretical “best-fit” for security measures, it is rarely ideal in a secure environment where a preference for either low FAR or FRR exists (Cope, 1990).

#### **2.4.1 Continuous supervision**

While the techniques outlined in the previous section are usually used to identify an individual at the start of a session (in a similar way to passwords) this does not address the problem of on-going authentication. In most systems, once a user has identified themselves to the operating system/application, it is usually impossible to determine if the active user is authorised. For example, a typical user session commences when they arrive in the morning and will end when they leave in the afternoon/evening. Throughout the day, the user will leave their terminal (often without any form of locking or password protected screen-saver) for breaks, lunch, meetings etc. During this period of absence, the system, without additional controls, will continue to assume that the user is still the original authenticated user – who could have been replaced at any stage by an impostor or masquerador. Whilst this may be adequate for some users, in environments where a higher level of security is required, some form of ongoing user authentication may be desirable.

To remedy this, authentication can be extended beyond the login stage and effectively supervise the user throughout a logged-in session. It should be noted that not all of the measures described above (and in the following sections) are suitable for continuous user monitoring. For example, signature recognition would be entirely unsuitable, as the user would be forced to stop his/her work to sign their name before proceeding. Instead, measures such as continuous keystroke analysis, combined with strong one-off authentication measures may prove effective.

### **2.4.2 Finger scan**

Fingerprint scanning requires a hardware-based device linked to a PC or access control system and is one of the most established forms of biometric based user authentication. The use of fingerprints as a means of identification has been established over many years through their use in criminology. Whilst this measure is a good discriminator of identity, there are social issues to consider. It has been suggested (IBG, 1999; Sherman, 1992) that the use of fingerprints for identification has criminal overtones and that there may be some resistance by users to use such systems. Despite this, there have been successful trials with organisations like MasterCard and the US Department of Defence (Identix, 2004) and these devices are now available at relatively low cost from a range of suppliers.

### **2.4.3 Hand geometry**

Hand geometry is, like fingerprints, a good discriminator of identity and also requires some form of dedicated hardware. It is one of the least used of all biometric measures, although

there are a number of establishments that have adopted it (Recogsys, 2003). Although there is little resistance to this form of user identification, it still requires a specific action on the part of the user, i.e. the user must place their hand on the scanner, there are also significant cost factors to consider for any deployment. While this seems to be accepted for access control for buildings, offices etc., it is unlikely to be acceptable on individual PC's or other devices.

#### **2.4.4 Retina scan**

Retinal scanning projects a laser light onto the user's retina and identification is based on the retinal vascular pattern i.e. the vein pattern on the retinal surface. There is only one commercially available system (Eyedentify from Access Controls International), their device claims to match a users retinal scan from a user base of 300,000 in less than 15 seconds (ACI, 2004). The accuracy of this device is claimed to be very high, this allows a user to simply present their eye to a device without requiring a card, pin or username, i.e. one to many identity matching. The main drawback to this device is cost and acceptability. The cost factor has restricted the use of such identification methods primarily to the military sectors, where security is of greater importance than cost. The acceptability factor is related to public perception of the safety of lasers. There are also some technical problems when identifying user's wearing glasses (especially if darkened) (ACI, 2004).

#### **2.4.5 Iris scan**

Iris scanning is also a hardware-based technique, using high-quality cameras and natural light to detect and identify the unique patterns of a users' iris. Iris scanning has several

advantages over retinal scanning, notably, cost and acceptability. The entry-cost for iris scanning is significantly cheaper than retinal scanning as it relies on simpler cameras e.g. Panasonic's Authenticam (Panasonic, 2004). As these cameras become more widespread (even potentially built into monitors), the use of iris scanning as an acceptable method of user identification may increase. Secondly, because the iris can be identified without the use of laser light, it may prove more acceptable from a safety viewpoint. Recent improvements have resulted in much more reliable products that are able to cope with users who wear contact lenses or glasses (Khew, 2002)

#### **2.4.6 Facial geometry**

Facial recognition is another economically viable method currently available. Facial recognition can be achieved using standard cameras e.g. a webcam. The video stream is then encoded and the face located and identified. The face can be authenticated using a range of methods but can be represented by two techniques. Feature extraction and recognition identifies the location of key features of the face (e.g. eyes, ear, nose and mouth) and calculates a geometrical relationship between the key features. This relationship is then stored as a mathematical model of the face. This method has the advantage that it relies on relative positioning of facial features and is therefore more tolerant of variations in head position. An alternative is to use a holistic approach where the face is evaluated as a whole and use neural networks or statistical techniques to evaluate a face-print and form a profile. As with iris recognition, there are some technical problems with user's appearance, e.g. wearing glasses, changing hairstyle etc., such deviations from the stored images may require the user's profile to be updated (Woodward et al, 2003).

### **2.4.7 Key stroke dynamics**

Keystroke dynamics can provide an additional level of security for the traditional username/password by analysing the typing style during logon, or, can be used to identify the user based on more dynamic freestyle text entry e.g. allowing the user to type a known string or phrase. This method is of particular interest as it is one of the few totally non-intrusive authentication mechanisms available as the user does not have to explicitly *do* anything to be authenticated by this method (i.e. the user would perform a normal login, or, in a supervised environment, would continue with routine tasks whilst being monitored in the background). There is only one available product that utilises this method, namely BioPassword (2004). This product is able to supplement login authentication with keystroke analysis – however, this is only at login and there is no further improvement in security beyond the initial authentication.

### **2.4.8 Mouse Dynamics**

Mouse dynamics is an extension of the keystroke analysis concept. The principle of mouse dynamics is that, like our typing, our mouse movements may be a characteristic trait that can be monitored and compared against a historic profile. Like the keystroke dynamics technique described previously, this method could also be transparent (depending on implementation) and could act as a continuous authentication mechanism. There are currently no products available using this technique.

### **2.4.9 Speaker verification**

Speaker verification requires nothing more than a basic microphone connected to the PC's sound card and the appropriate software. Speaker verification is a distinct area from that of voice interpretation that is commonly found in commercially available dictation software often (mistakenly) referred to as voice recognition (voice recognition/interpretation software is used to convert spoken language into written text – i.e. a speech-text translator and has no recognition of the individual speaker). Whilst this is a conceptually simple form of user authentication, it may be inappropriate in certain (noisy) environments.

### **2.4.10 Dynamic signature**

Of all the biometric measures, signature recognition is probably the most familiar to the end-user. The principle of providing a signature as a means of authentication is a historical part of western culture – thus potentially avoiding some of the problems of acceptability. However, it should be noted that this would be one of the most intrusive biometric-based authentication techniques if applied in a continuous context, requiring a user to stop work and sign their name. A significant advantage of signature recognition over keystroke analysis or voice recognition is avoiding the dependency on technical ability or language. However, there is also the need for a signature capture device – typically provided as a graphics tablet.

### 2.4.11 Summary of techniques

Each of these methods of enhancing user authentication has advantages and disadvantages. Perhaps the most significant of these is the user acceptance of such measures. To determine the level of user acceptance, a survey was carried out, the details of which are listed in chapter 3. There are also other issues to consider, specifically, effectiveness, transparency and cost. These were not considered as part of the survey as the majority of the respondents would not have the adequate knowledge in the area to provide appropriate responses. The benefits and disadvantages of each of these methods are briefly described in Table 2.6. False Acceptance/Rejection Rates are also shown (where available). Unfortunately it is often difficult to gather sufficient quantitative data from the biometric manufacturers. In particular, mouse dynamics has been omitted from this table, as there are no commercially available products to evaluate.

It is interesting to note that hardware/software vendors seem to ignore the only statistical analysis of the effectiveness of biometric authentication methods. In fact a number of vendors stated the error rates for their products as “low”, an entirely subjective assessment. This apparent ignorance of the appropriate measures may further hinder the acceptance of these methods into both commercial and private sectors.

There are few standardised methods of comparison between biometric authentication measures. However, a method used by the Independent Biometric Group (IBG) is the Zephyr™ chart, which shows the authentication methods around the outside with the assessment criteria ranked inside the chart. The evaluation criteria used are listed in Table 2.7.



| Method                              | FAR                                                    | FRR   | Advantages                                                                                        | Disadvantages                                                                                                                       |
|-------------------------------------|--------------------------------------------------------|-------|---------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Password                            | Not Applicable                                         |       | No hardware requirements.<br>Transparent to user.                                                 | Users forget, share and write down passwords. Selection of passwords is usually poor (names, places, dictionary words etc.)         |
| Keystroke analysis [BioPassword]    | 0.68%<br>Equal Error Rate                              |       | No hardware requirements.<br>Transparent to user.                                                 | May not be suited to certain typists (touch).<br>Not appropriate in certain industries (graphics).                                  |
| Face recognition [Miros]            | "Low"                                                  | <0.2% | Simple to use.<br>Camera can be integrated into monitor                                           | Camera required.                                                                                                                    |
| Voice verification [Motorola]       | 1.07% 1-Phrase<br>0.2% 4-Phrase<br>[Equal Error Rates] |       | May be ideal for switchboard/VoIP based systems.<br>May be effective for telesales/phone banking. | Requires audio hardware.<br>May not be suitable in office environments (intrusive to other users) or industrial (background noise). |
| Signature analysis [PenOp]          | Variable<br>Not Quoted                                 |       | User familiarity with concept of signatures for ID may help acceptance                            | Requires signature device.<br>Intrusive.                                                                                            |
| Iris scanning [IriScan Inc.]        | 0.0001%<br>[Equal Error Rate]                          |       | High level of user discrimination.                                                                | Requires scanning device.<br>Intrusive.<br>Acceptability may be hindered by confusion with retinal scanning (laser).                |
| Retinal scanning [Eyedentify Inc.]  | 0.0001%                                                | 0.1%  | High level of user discrimination.                                                                | Requires scanning device.<br>Intrusive.<br>Uses laser light which may worry users.                                                  |
| Hand geometry [Recognition Systems] | 0.15%                                                  | 0.15% | Simple to use.                                                                                    | Requires scanning device.<br>Intrusive.                                                                                             |
| Fingerprint analysis [Compaq]       | 0.001%                                                 | 0.5%  | Simple to use.<br>Hardware becoming cheap (<£100).                                                | Requires scanning device (relatively cheap).<br>Intrusive.<br>Criminal connotations (fingerprinting)                                |

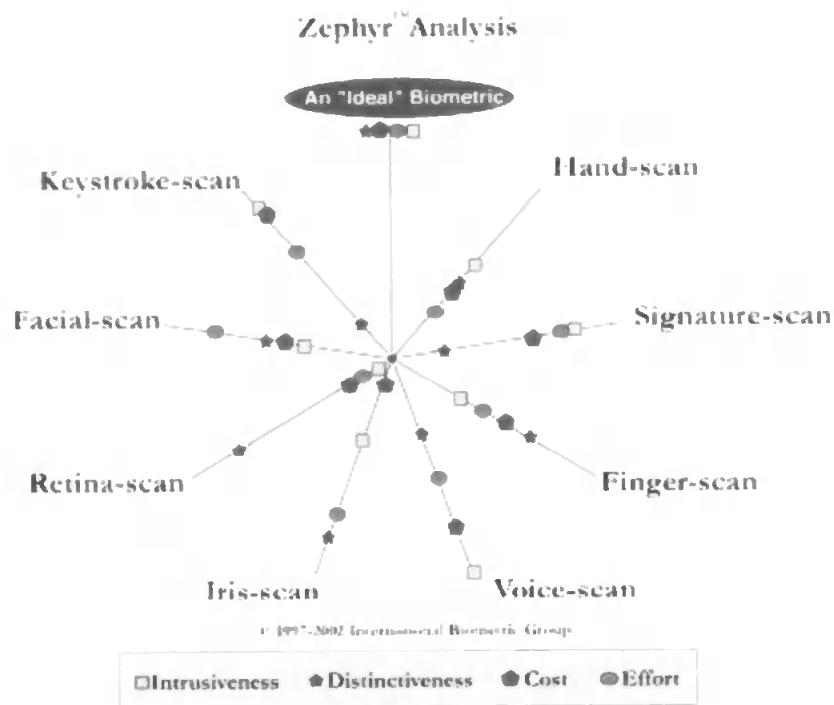
Table 2.6 - Comparison of commercially available authentication methods

| User Criteria<br>Aspects which relate to the user.                                                                            | Technology Criteria<br>Aspects which relate to the technology                                                             |
|-------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| 1. <b>Effort</b> - How much time and effort is required on the part of the user i.e. registration, enrolment, authentication. | 1. <b>Cost</b> - Cost of any necessary hardware capture device together with any software, support and training required. |
| 2. <b>Intrusiveness</b> - How intrusive the user <i>perceives</i> the system to be.                                           | 2. <b>Accuracy</b> - How well the system identifies individuals. [FAR/FRR]                                                |

Source: International Biometric Group (2002)

Table 2.7 - Table of evaluation criteria used in Zephyr chart

A Zephyr chart allows the comparative strengths and weaknesses of each measure to be examined visually. As an example, Figure 2.3 shows a Zephyr chart available from the International Biometric Group (IBG,2002). The ideal criteria for a successful biometric measure is shown at the top of the chart, (this only occurs when all four criteria are at their optimum settings and are, therefore, located at the outer perimeter of the chart).



Source: International Biometric Group (2002)

Figure 2.3 - Zephyr™ Chart for common biometric-based authentication methods

If we consider the use of keystroke dynamics, the criteria are distributed across the entire range (it should be noted that this is based on one-off authentication rather than continuous monitoring). Of the four criteria, keystroke analysis satisfies two, namely non-intrusiveness and cost. Many biometrics fail on the intrusiveness criteria as they require the user to perform some explicit action to authenticate themselves. Static keystroke analysis offers the ability to analyse keystroke patterns during the entry of the username/password pair (or some other form of identification string) therefore reducing the

impact on the user. Cost is minimised (as far as hardware issues are concerned) as almost all PCs will have a keyboard, although there will be some additional expense as a result of additional costs (i.e. training, maintenance etc.). The effort involved to authenticate via keystroke analysis is still small in comparison to some other methods as the user is only required to type in a small sample of text. Ideally, this would be enhanced to monitor free-style text, thus further reducing the effort involved to achieve authentication by this method. The final criterion is that of accuracy. Static keystroke analysis is ranked comparatively poorly against the other methods; this is mainly due to the limited amount of data with which user authentication can take place and the variability likely with such a small sample size.

## **2.5 Conclusions**

This chapter has presented the increase in levels of detected computer crime and abuse cases over the last twenty years (as reported within the UK). Although it is not possible to attribute the increase in reported crime to any underlying specific cause (i.e. was the rise due to increased criminal/malicious activity, increased reporting of crimes or the increased success in detecting and solving such cases) it is clear that there is an increased level of incidents with a respective increase in costs.

One of the problems in addressing the increase in crime is that of attributing blame. The surveys presented have indicated a high level of cases originating from within organisations however, in order to identify the person or persons responsible for the incident, it is necessary to have absolute authentication of a user's identity. A misfeasor

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would be acting under their own account with appropriate permissions and hence would not be highlighted by the usual authentication measures, while a masquerador may only be detectable through improved authentication techniques. Given that many users leave their terminals logged in and unlocked for long periods of time (usually all day), simple login authentication is not sufficient.

This chapter has also discussed the limitations of current authentication techniques, highlighting in particular the shortcomings of the commonest method – the username/password combination. To overcome these problems a number of alternatives have been presented together with an overview of their advantages and disadvantages.

It is clear that some form of improved authentication is necessary to ensure accurate authentication at login. It is also important for the concept of monitoring to be considered to ensure that the active user is the original user who logged in – i.e. continuous user authentication/monitoring.

Before investigating potential improvements to user authentication, a survey was conducted to determine the need for improved user authentication and supervision, and to determine the user acceptability of such measures (which would help to inform the design and implementation of an improved user authentication and supervision system). This survey is described and discussed in the following chapter.

## **Chapter 3**

### ***A Survey of User Attitudes and Perceptions***

### **3.1 Introduction**

The previous chapter identified the weaknesses of current authentication systems and proposed a number of alternatives to the current secret-based approaches. Before attempting to implement and evaluate alternatives to the traditional username/password approach, it is first necessary to determine the attitudes of computer system users to the current methods of authentication, as well as their perceptions of the alternatives presented in the previous chapter. This is increasingly important as users frequently find ways to bypass security mechanisms that are considered to be inconvenient or intrusive.

This chapter presents the results of a survey that aimed to determine awareness, and acceptance of, a range of alternative authentication and supervision methods. The survey respondents were asked to comment on current techniques, identifying bad practise (e.g. sharing passwords), as well as mitigating circumstances (e.g. large numbers of passwords for different systems), before considering a number of alternative authentication mechanisms.

### **3.2 Survey Overview**

In order to determine the acceptability of user authentication and supervision techniques, a survey was conducted to assess the attitudes and awareness of current IT users. The survey aimed to assess the following issues:

- attitudes towards different forms of user authentication;
- the attitudes towards the concept of continuous monitoring.

The survey questionnaire consisted of 53 main questions, the majority of which were multiple choice, with the remainder requiring short written responses (a copy of the paper-based questionnaire can be found in Appendix A). Many of the questions contained multiple sections, resulting in a maximum of 130 possible answers per respondent. The survey was split into a number of categories, each focussing upon a specific area of interest. Questions 1-7 gathered general details, to determine the gender, age, education, and level of computer use; these provided demographic information on the survey response base. Questions 8-14 considered the use of computers within the respondent's work environment, whilst questions 15-19 considered the use of computers at home. These helped to provide information on the spread of IT into the home and work contexts, as well as the likely IT awareness of the respondents. Questions 20-34 were intended to determine individual opinions and knowledge in the area of computer crime and abuse. The findings relating specifically to these questions are presented in Dowland et al (1999) and will not be discussed here. The final section (encompassing questions 35-53) looked at the respondent's views on user authentication and supervision.

The survey was distributed to a wide range of individuals and organisations with the intention of gaining a diverse variety of opinions. The questionnaire was made available in two forms, a printed copy and an online version. Approximately 300 printed surveys were distributed with 148 completed responses being received, representing a response rate of 49%. A further 27 responses were submitted via the web site resulting in a total of 175 responses. It should be noted that, whilst questionnaires were sent to companies, the focus of the questionnaire required respondents to reply from an individual rather than organisational perspective (i.e. respondents were asked to consider the questions posed from a personal perspective rather than considering an organisational security policy –

should one exist). As such, these responses were still representative of a personal rather than business viewpoint on the issues.

### 3.3 Demographics

The survey demographics showed a male dominance in all age groups, with 80% of the total respondents being male. In terms of age, 74% of the respondents were below 35, indicating that the vast majority of the responses were likely to be from people who had grown up with IT to some extent. The overall breakdown of respondents by age group is given in Figure 3.1.

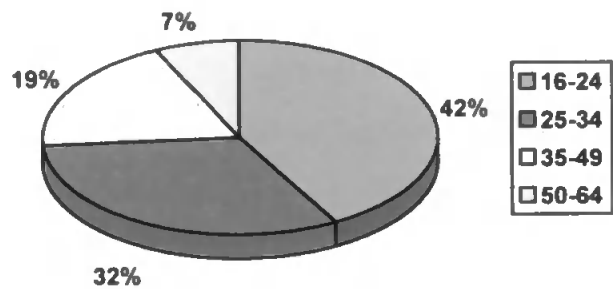


Figure 3.1 - Survey respondents by age

In terms of employment background, a high number of responses were received from the technology fields (with 103 out of the 175 responses claiming to be from the computing, communications or engineering domains). Academically over 70% of the respondents claimed to hold A-Levels or above, with 44% having a degree level education. This represents a generally high level of academic achievement and reflects the fact that the distribution of a large proportion of surveys occurred via academic channels.

The vast majority of respondents had considerable familiarity with IT, with over 98% having used a computer for over 1 year, 88% using a computer at work and 84% using one



at home. In terms of the level of use, the results indicated that, in both home and work environments; over half of the respondents used their systems for four hours per week or more. The respondents were also asked about the availability of Internet access. 129 respondents (88%) claimed to have access at work, while 69 respondents (48%) claimed to have access at home. The latter statistic indicated that the respondent group was clearly ahead of the UK average in terms of Internet adoption, as the penetration into UK homes (at the time of the survey) was considered to be around 14% (ICM, 1999). It should be noted that more recent surveys have estimated UK Internet adoption at around 50% (Ofcom, 2003), which would be more in-line with the respondents from this survey.

The general information above shows that the respondents had considerable experience using computers in both home and work environments. As such it was considered that the respondents had adequate background knowledge in order to comment on a range of authentication techniques and the issues relating to them.

### **3.4 Password based authentication**

Given that they represent the most common, and therefore familiar, form of authentication, the survey began by assessing respondent attitudes towards passwords. The results indicated that over 91% of respondents relied on passwords for access control to their computers – a figure that is generally compatible with the 1998 KPMG security survey which showed 97% of organisations using them (KPMG, 1998). This situation appears to have changed relatively little since the survey was completed, with the latest DTI survey (DTI, 2002) reporting between 82% and 99% of organisations still using passwords for user authentication (the precise figure varies by organisational size). The high reported use

of passwords among respondents ensured that the subsequent questions about password implementations and password limitations would be answered based upon practical experience.

Due to the dominance of passwords, most users have multiple passwords for different systems and applications. When asked how many different systems or applications they use which require passwords, 26% of respondents claimed to have five or more, with 18 people claiming in excess of ten (Figure 3.2). This is becoming an increasingly problematic issue due to the increased usage of web-based systems. With the spread of on-line banking, e-commerce and login details needed for a wide range of sites, an average user may have numerous username/password combinations. Added to this, many web sites have specific requirements for the format of usernames/passwords. These requirements may include the familiar minimum length requirements, but they are increasingly requiring mixed case, punctuation or numeric characters to occur in login details (especially in the on-line banking sector). It is likely that the number of systems that users will be required to authenticate themselves to will only increase over the coming years.

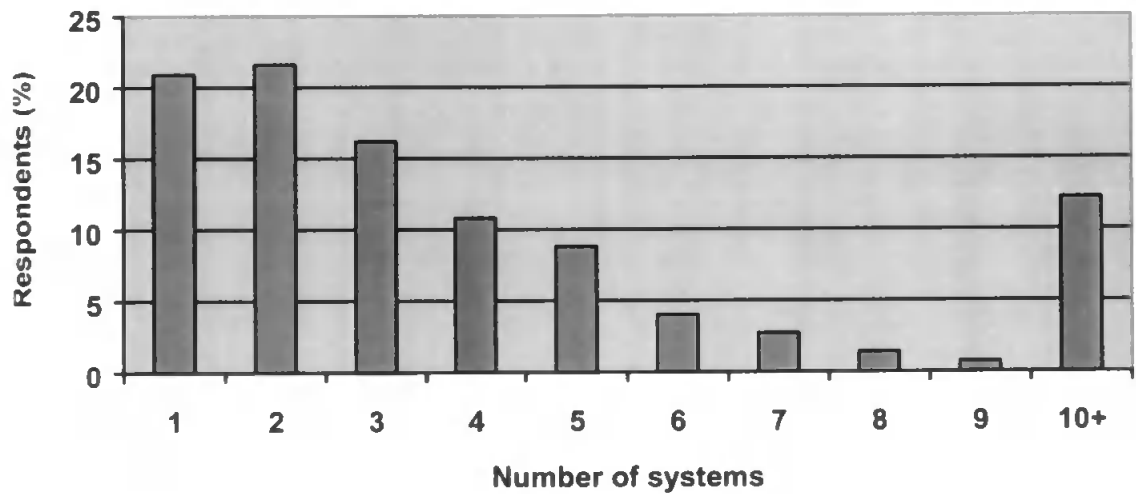


Figure 3.2 - Number of different systems/applications used requiring passwords

The requirement to remember such a large number of passwords can cause a major problem for users. It is, therefore, no surprise that users frequently select dictionary words or personal names as the basis for their passwords, as these are easier to remember. Having said this, only 15% of respondents felt that their passwords could be easily guessed. The phrasing of the question in this case gave examples of information that, if used as a basis for selection, could render the password more easily guessed (i.e. “is it part of your address, name, partner’s name?”). Although the majority of users considered themselves to be safe on this basis, the question did not provide an exhaustive list of what might constitute obvious choices. As such, many respondents may still have been using insecure passwords, such as dictionary words (which the L0phtCrack tool mentioned in the previous chapter can determine in less than a minute). It should, however, be noted that even when forced to select more complex (and hence less meaningful) passwords, users often compromise these by writing them down (15%) or sharing them with other users (29%). This is not always done without any thought to the consequences, but for some users, the benefits of having a note stuck to the monitor of their PC with their password in clear sight for all to see is better than the problems caused by forgetting the password every four weeks due to forced password changes!

Not only do users often choose insecure passwords, they also frequently select the same password for multiple accounts, with 40% of respondents re-using the same password. As such, should an intruder gain access to one protected account, it is quite likely that they would be able to reuse that same password for other machines and applications. This could be extrapolated further when considering the impact upon web site logins – if users choose the same (insecure) login details across multiple sites, it is likely that a successful intruder on one site would have unrestricted access to a wide range of sites. Responses to

subsequent questions revealed that 31 (21%) of the 151 respondents who used computers at work claimed to have used another person's password without their consent or knowledge. It is surprising that so many people have illegitimately used other users' accounts and also to find that so many of the respondents were prepared to admit to doing so. It is possible that some of the respondents lied about such illegitimate activity and, as such, the real figure could be somewhat higher. It could be argued that if respondents had taken better care of their passwords (by following basic guidelines on selection and use) it is likely that there would have been less opportunity for such abuse.

A further issue is that of the password's lifetime. Once a password is illegitimately acquired then, without time limits, restricted logins or account monitoring, it is possible that the intruder would remain unnoticed until he/she committed an act that caused some form of disruption that would consequently be detected. If we again consider the use of web sites, a compromised account could provide not only unrestricted access (if no time limits were imposed on accounts) but, more worryingly, could provide unlimited access to other accounts sharing the same login details. The respondents were asked how frequently they changed their passwords and if they were forced to change their passwords by the system or the system administrators. As indicated in Table 3.1, an alarming 34% claimed to never change their passwords. Furthermore, the responses to the subsequent question revealed that 51% were not forced to change their password by the system. The former represents bad practice on the part of the users, whereas the latter reflects poor system administration. From an administration point of view, it is more encouraging to observe that 70% of users claimed to use systems in which a minimum password length is enforced. Having a minimum length of seven or more characters helps to ensure that passwords are more resilient to brute force attacks.

| Frequency of password change | Respondents |
|------------------------------|-------------|
| Weekly                       | 2%          |
| Fortnightly                  | 1%          |
| Monthly                      | 25%         |
| Six-monthly                  | 18%         |
| Less frequently              | 20%         |
| Never                        | 34%         |

**Table 3.1 - Frequency of password changes**

These results serve to underline some of the known problems with passwords and provide the justification for the subsequent questions, which asked users about other forms of authentication.

### **3.5 Alternative authentication and supervision methods**

One of the main objectives of the survey was to evaluate user's opinions regarding different authentication methods. In order to achieve this, the respondents were asked to rate the acceptability of a variety of initial login and continuous supervision techniques on a 5-point sliding scale from 'totally acceptable' to 'totally unacceptable'. A total of nine methods were cited, ranging from passwords to a variety of physiological and behavioural biometric methods. Each of the methods was briefly described on the questionnaire sheet to ensure that the respondents understood the context (using the text shown in Table 3.2).

| Method               | Description                                                                                                                           |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Keystroke analysis   | Research has shown that users have different typing styles and that they can be identified by measuring the times between keystrokes. |
| Face recognition     | A snapshot of the user, taken by a camera positioned on the monitor, is compared with a previously stored 'faceprint'.                |
| Mouse dynamics       | Similar to keystroke analysis, users can be identified by the way in which they use the mouse.                                        |
| Voice verification   | A user's voice, when speaking a word or phrase into the computer's microphone, is compared with a previously stored 'voiceprint'.     |
| Signature analysis   | A user signs their name using a special pen and pad, the signature is digitised and compared with a previously stored version.        |
| Iris scanning        | A snapshot of the user's iris, taken by a camera, is compared with a previously stored image.                                         |
| Hand geometry        | This technique measures the physical dimensions of the hand using a small camera and compares these with previously stored values.    |
| Fingerprint analysis | An automated version of the fingerprint identification system similar to that traditionally used in criminology.                      |

Table 3.2 - Biometric methods, as presented to survey respondents

Table 3.3 summarises the ranked results, which are also illustrated graphically in Figure 3.3. The responses have been normalised to reflect the variable response rate to each question, as there was a higher response rate to questions on initial login authentication (probably reflecting a lack of understanding of the concept of continuous supervision amongst some respondents). The positive responses ('totally acceptable' and 'acceptable') were summed and then the total number of negative responses ('unacceptable' and 'totally unacceptable') were subtracted, thus producing a rank of user preference.

| Method               | Initial login authentication | Continuous supervision |
|----------------------|------------------------------|------------------------|
| Password             | 95.7%                        | -10.2%                 |
| Keystroke analysis   | 29.8%                        | 25.5%                  |
| Face recognition     | 49.1%                        | 3.2%                   |
| Mouse dynamics       | 21.3%                        | 21.8%                  |
| Voice verification   | 53.4%                        | -0.6%                  |
| Signature analysis   | 40.1%                        | -35.9%                 |
| Iris scanning        | 47.2%                        | -16.8%                 |
| Hand geometry        | 44.4%                        | -19.9%                 |
| Fingerprint analysis | 48.8%                        | -16.0%                 |

Table 3.3 - Ranked user preference of security methods

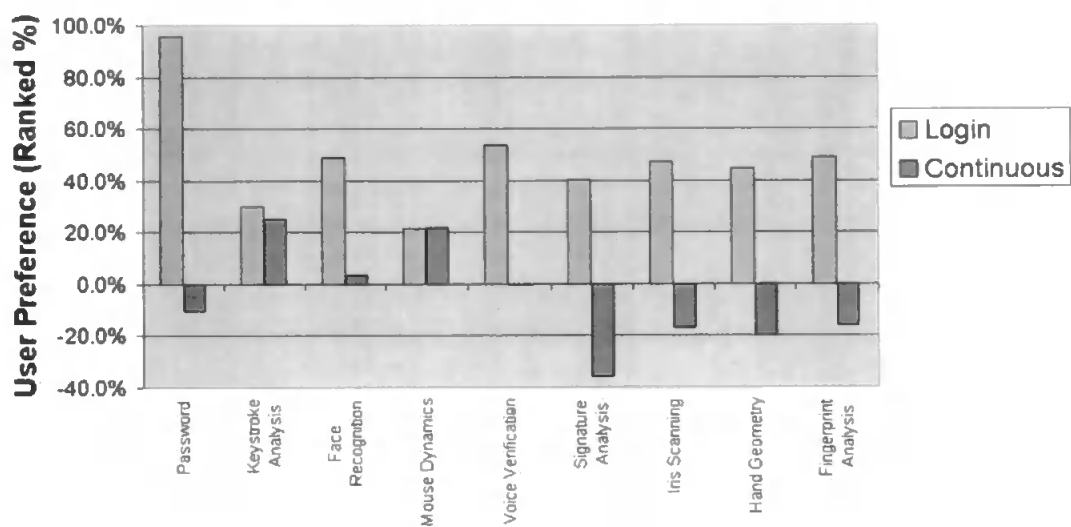


Figure 3.3 - User preference of authentication methods

As expected, the most popular form of initial login authentication was the password, with 90% of respondents rating it as ‘totally acceptable’ (scoring more than twice as many votes in this category than most other methods). However, it should be noted that if all respondents were forced to adopt correct password selection and use procedures, it is considered unlikely that the level of acceptance would be quite so high. This high level of acceptance for passwords did not mean the outright rejection of alternative methods and many also achieved respectable scores.

It is clear that there is a reasonably significant level of user acceptance for all the initial login authentication techniques suggested. Methods such as face recognition, voice verification, signature analysis, iris scanning, hand geometry and fingerprint analysis were all considered favourably. It is interesting to note that all of these techniques (with the exception of signature analysis) have had significant media coverage, especially through film and television. It is possible that familiarity with these techniques influenced the respondents' choices. The acceptance of signature analysis cannot be readily explained by the familiarity with the technology through the media; however the concept of a signature as a means of identity verification is well established in our society.

After passwords, the most acceptable forms of login authentication were considered to be voice verification and fingerprint recognition, scoring raw overall acceptability ratings of 68% and 67% respectively (full table of results in Appendix A). The latter result is somewhat surprising, in that conventional wisdom suggests that the association of fingerprints with criminal identification may represent a potential barrier to user acceptance (Observer, 2002). However, it is clear from these results that the majority of respondents are comfortable with the concept. It can, however, be noted that, in the normalised results (Table 3.3), face recognition scored higher than fingerprints once negative responses had been taken into account (un-normalised results can be found in Appendix A). It should be considered that while these results show a positive response to the use of such techniques, the respondent base was predominantly represented by IT-literate, well-educated individuals working regularly with PC's. As such, it is perhaps unsurprising that a high level of acceptance was achieved. If a wider (more inclusive) survey were conducted, it is possible that certain techniques (e.g. fingerprint scanning or retinal scanning) may have achieved lower acceptance for login authentication due to public distaste for such mechanisms; while others (e.g. keystroke analysis and mouse



dynamics) may have had a lower acceptance due to lack of exposure or knowledge of the techniques.

One of the significant questions posed in the survey was whether respondents would be comfortable with the concept of continuous supervision. This would provide a means for authentication to become an ongoing process within a logged in session, rather than being merely a one-time judgement at the beginning. This, in turn, would guard against situations such as an impostor replacing a legitimate user at the terminal, or an impostor who may have been able to fool the initial login authentication system. In general, the respondents were positive towards the idea of monitoring, with 43% considering it acceptable, though 29% were unsure. It is, perhaps, unsurprising that there was some reluctance – if continuous monitoring were deployed in an organisational context, employees may be concerned about the use of data gathered by such techniques. For example, if keystroke analysis were used to monitor a users' typing, the statistics could be used to profile a users' productivity or to confirm when the user was at his/her desk. It is also possible that an employer (or administrator) could use keystroke analysis software to actually record the typing of an employee and then obtain potentially sensitive/private information (e.g. on-line banking details). Safeguards and other concerns are discussed later in this section.

It is recognised that the concept of continuous supervision also introduces ethical considerations. Indeed, 70 respondents (40%) stated that they would consider monitoring as an invasion of their privacy (interestingly, 18 of these had stated that they considered this to be acceptable), with a further 18% being unsure. It is clear that if continuous supervision of users is to be implemented, then certain safeguards should be considered. In

particular, users should be aware of the intended uses of the information collected. 45% of respondents felt that they could not trust their organisation to use the supervision data for security-related purposes only, and were concerned that it could be utilised for an ulterior motive, such as monitoring work productivity. 85% stated that users should be aware of any monitoring being used, potentially demonstrating an inherent distrust of the concept of a big-brother scenario. The simplest way to ensure these requirements are met is to involve the users in the planning and implementation of these systems and provide clear policies on the uses for the gathered information. With the introduction of data protection laws covering personal information stored electronically there will also have to be provision for securing the profiles and session data obtained in any continuous monitoring system as well as ensuring access (upon request) to all personal data stored in the system (in the same way that an employee may ask for his/her personnel records).

The respondents considered only three techniques to be acceptable for continuous monitoring; namely keystroke analysis, mouse dynamics and face recognition (the latter being with a very low preference). Whilst the overall ranked results reflected sensible views, some of the individual responses in the underlying data did provide a few surprises. In particular, 34 respondents rated the use of signature analysis for continuous monitoring to be 'acceptable'. This is most likely to be a misunderstanding, as few computer users would be prepared to stop work and sign their name intermittently (a view borne out by the fact that 90 respondents rated this as 'unacceptable').

Respondents were also asked to consider how long they would be prepared to spend creating a behaviour profile that the monitoring system would then use to authenticate them. The responses are shown in Table 3.4. It is clear that the majority of users would

not be tolerant of explicit profiling activity for any long periods. Equally, the time that most of them would consider acceptable is 15 minutes or less – which would be unlikely to be adequate for some measures (e.g. whilst face and fingerprint recognition systems would allow adequate registration within this time, accurate measures relating to typing and more general system usage would require longer periods – potentially in the order of days rather than minutes). As such, elements of profiling would need to occur as a transparent background task in order to ensure user acceptance.

| User-profile set-up time | Respondents |
|--------------------------|-------------|
| No time                  | 11%         |
| Up to 5 mins             | 36%         |
| Up to 15 mins            | 24%         |
| Up to 30 mins            | 13%         |
| Up to 1hr                | 12%         |
| > 1hr                    | 5%          |

**Table 3.4 Acceptable duration of profiling activity**

Once a profile has been created, there is still the possibility that a monitoring system may falsely reject a legitimate user, believing them to be an impostor. The questionnaire made the respondents aware of this and asked them how frequently they would be willing to tolerate such errors. The results are presented in Table 3.5 and illustrate that any deployed system would need to have a very low error rate in order to avoid alienating the user population.

| Frequency of false rejection | Respondents |
|------------------------------|-------------|
| Hourly                       | 7%          |
| Daily                        | 27%         |
| Weekly                       | 36%         |
| Never                        | 29%         |

**Table 3.5 Perceived tolerable frequency of false rejection by monitoring system**

Finally, the respondents were asked to indicate which fields/sectors would benefit most from supervision of users by computer, rating the benefit from ‘great benefit’ to ‘no benefit at all’. As with the results in Table 3.3, the responses have been normalised to provide a ranked overall benefit. The positive responses (‘great benefit’ and ‘some benefit’) were summed and then the total number of negative responses (‘little benefit’ and ‘no benefit at all’) was subtracted, thus producing a rank of overall perceived benefit. These results are shown in Figure 3.4.

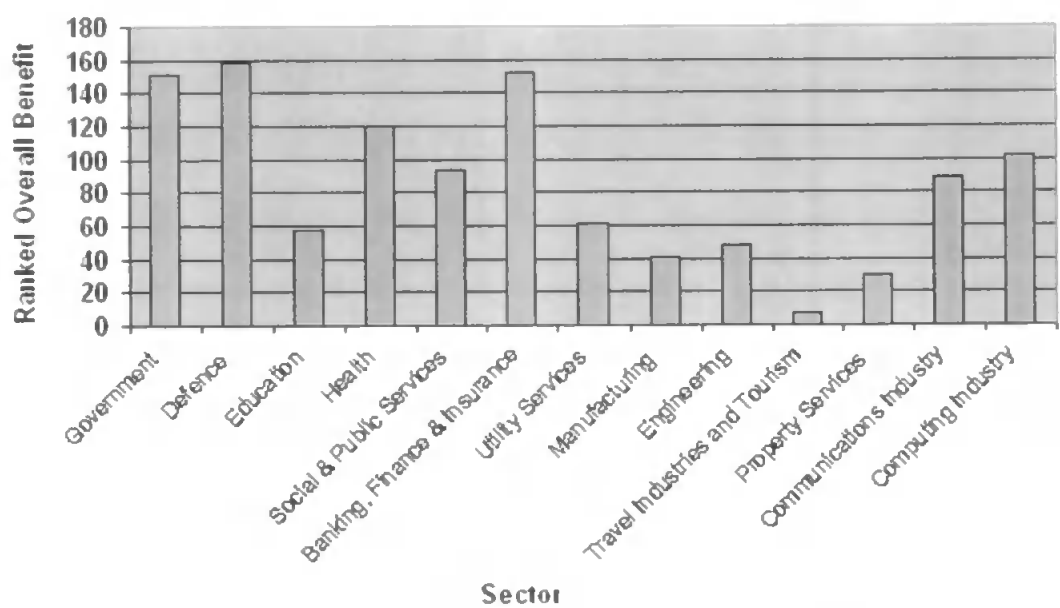


Figure 3.4 - Benefit from monitoring by sector

As expected, the majority of respondents considered the areas of government, defence, health and banking to benefit most from user supervision (these being the areas with the most obviously sensitive systems and data to protect). However, the respondents felt that all areas could benefit from improved supervision, showing that there is still considerable concern over the perceived level of computer security across all sectors.

### **3.6 Discussion of results**

The results reaffirm the accepted shortcomings of password-based authentication (poor selection, sharing and forgetting passwords etc.), as well as the fact that, in spite of these, it remains the dominant form of user authentication. However, the fact that the respondents have shown a willingness to use alternative authentication techniques can be considered to be encouraging. It should be noted, however, that in the majority of cases, it is unlikely that the respondents had actually used the techniques that they were being asked to comment upon. As such, it is possible that their views may change if presented with the practical experience.

Given that a strong preference was expressed for passwords, consideration should be given to retaining them as the means of login authentication, whilst identifying means to compensate for their weaknesses. Suitable strategies in this respect could include (with numerous other combinations):

- Utilising password login in conjunction with transparent keystroke analysis of the information entered. In this way, the user would be authenticated not only by what they type, but also how they type it. This should not have any significant influence on user acceptance, as the primary authentication mechanism will still appear to be the password. This would, however, not overcome a fundamental problem of password-based system; that once logged in, there is typically no further authentication required throughout a users' session. A user may login at the beginning of the working day, providing a valid match is made between the typed password and the users' historical typing profile but

then be able to continue throughout the rest of the day without any form of challenge. While this approach enhances the initial login authentication, it provides no further session protection. Given that many users leave their workstations logged in all day (with some not even logging out when they leave in the evening), this would only be able to potentially catch another user misusing a colleague's details at login. While this offers no protection during the logged-in session, it does represent a significant improvement over login authentication.

- Retaining password-only authentication at login, but supplementing it with on-going supervision during the user session. (NB the term continuous is used to distinguish between static monitoring; e.g. monitoring key presses during login, and dynamic monitoring which has the ability to monitor a users' behaviour throughout a session – the time interval for which could be truly continuous or intermittent.) The survey results suggest that techniques such as keystroke analysis and mouse dynamics would be conceptually acceptable to users in this regard. This approach could still retain the user-accepted login mechanism (i.e. username and password), but would switch to a supervision/monitoring role once the user had been authenticated; to monitor the users' typing behaviour, application usage or mouse dynamics (or some other metric) throughout the logged-in session. This would effectively remove the ability for a third party to hijack the users' session providing the resolution of the monitoring was sufficient to identify an impostor within an acceptable time frame.

The respondents preference for passwords is in agreement with the previously published results from the Australian TRUST project, which (based on an experiment with 76 participants) found users' principal preference to be for passwords, followed by physiological biometrics and, finally, behavioural measures (Deane et al, 1995). The latter finding is, however, in contrast to the results from this study in that (for continuous monitoring) the behavioural techniques of keystroke and mouse dynamics were chosen in preference to the physiological technique of face recognition. Indeed, in the TRUST study, keystroke analysis and pointing device based verification scored the lowest of the seven biometrics assessed.

Although many considered the concept of continuous supervision to be acceptable for security purposes, the respondents showed concern over the potential wider use of such data. As such, it is important for organisations to establish agreed working practices to employees before proceeding with such methods (this may assist in reassuring those such as the 29% of respondents who were undecided over the acceptability of the monitoring concept). If such practices are not naturally adopted by organisations, it is possible (maybe even preferable in some cases) to legislate on acceptable supervision practices. This could be implemented in a similar way to that which restricts the rights of an employer to intercept and/or read an employee's email correspondence (HMSO, 2000).

Overall, a significant factor in the acceptance of alternatives to the password will be that of education. If people can be shown that newer authentication techniques are safe, reliable and secure, then their acceptance is likely to be improved. This will be best demonstrated in the UK over the next ten years where a trial is being undertaken to determine public acceptance of biometric identification. This scheme (Home Office, 2003), announced by

the government in November 2003, is due to begin in early 2004, with the aim of introducing a national identity card scheme comprising driving license, passport details and incorporating a biometric ID (iris or fingerprint scan). This scheme, more than any other in recent years, will depend on public acceptance to determine the widespread used of biometrics. If the public reaction to biometric identification is negative, it will be increasingly difficult to implement such systems – even when forced through employment contracts or government legislation.

Of course, the UK is by no means alone in considering the use of widespread biometric systems. The US has been trialling biometric systems at border points for some time now (ZDNet, 2002) and has recently announced plans to use fingerprint scanning for overseas workers entering the country (USDoS, 2003).

### **3.7 Conclusions**

The survey has shown that, although demonstrably weak, the password remains the most popular form of authentication in the minds of users. However, a number of other methods emerged as possible contenders, and it is possible that practical experience of using them, combined with improved awareness of the vulnerabilities of passwords, would increase their perceived acceptability as alternatives.

Another conclusion that can be drawn from the survey results is that the use of continuous supervision is, in general, acceptable. However, the viability of such a scheme would be dictated by the methods chosen, and subject to suitable assurances being given to the monitored population regarding the planned uses of the collected data. This is an



important issue as user acceptance of such a radical approach as continuous user authentication will probably be just as important as overcoming the technical issues of implementation. There are also potential problems with the level of user support needed to make these systems work. There may still be reluctance on the part of users to undertake the necessary profiling to make the systems used sufficiently reliable for day to day use, as well as resentment should the system reject valid users too frequently. The survey has also indicated a lack of understanding over authentication in general and the specific issues of continuous user supervision. It is unlikely that re-educating users will avoid the problems with passwords, however, it is possible that increased awareness and understanding could improve acceptance of alternatives.

Given the acceptance of some form of supervision during a logged-in session and the preference for a keystroke-analysis based method, the latter parts of this thesis will discuss the application of transparent keystroke analysis in a modern operating system. Chapter 5 will introduce in more technical detail the concepts of keystroke analysis and identify the range of metrics that can be assessed, while chapters 6 and 7 evaluate the results of two trials conducted to ascertain the feasibility of a keystroke analysis based supervision system.

Before committing to keystroke analysis, the next chapter presents the results of some further investigations that were conducted in order to determine whether the weak, password-based approach could be more easily replaced by an alternative secret-based knowledge approach to user authentication.

## **Chapter 4**

### ***Assessing Alternative Methods of User Authentication***

## **4.1 Introduction**

The survey described in the previous chapter identified the need for improved user authentication, with the respondents indicating a continued preference for secret-based authentication (e.g. the use of passwords). Unfortunately, although users may still have a preference for passwords, the weaknesses of this method are well known. In order to provide improved security, while still maintaining the users' preference for a secret-based approach, this chapter considers the results of two trials conducted to investigate alternative forms of user authentication using software-based methods (which do not incur any additional expenditure on hardware technologies, and as such are likely to be considered favourably by system administrators).

Previous research into alternative software-based methods has identified a number of potential approaches:

- Cognitive and associative questions – a question and answer based approach using easily memorable (but nonetheless secret) information (Haga and Zviran, 1991). This approach has a distinct disadvantage as it can require a lengthy exchange between the user and the system in order to be authenticated.
- Graphical authentication – this uses graphical images that the user must memorise and identify on screen. There are a number of implementations, ranging from a picture with a number of pre-defined regions (Blonder, 1996 and Jermyn et al., 1999) to the Déjà Vu system that used randomly generated electronic art images (Dhamija and Perrig 2000).

These methods share the common advantage of easy implementation – i.e. they are software based methods that have no hardware dependencies (unlike most biometric-based authentication methods that require dedicated hardware).

While previous trials have shown the individual techniques to be viable authentication measures, there have been no comparative experiments to evaluate user acceptance of these measures side by side. As such, two trials were conducted in order to evaluate the techniques. The first, described in the next section aimed to test users' recall of personal (but secret) information. The second trial, described in section 4.3, took a longer-term approach to evaluate user friendliness and acceptability. These trials allowed a comparison to be made between these techniques with users having similar levels of exposure to each method.

## **4.2 An Experimental Study Of Alternative Methods**

The first trial was devised to evaluate five secret-knowledge based techniques. The methods selected were PINs and passwords (familiar methods, included to provide a baseline for reference), alongside two question and answer methods (using cognitive and associative questions respectively), and a graphical technique using an image-based PIN (hereafter referred to as an ImagePIN). The study sought to assess the practical effectiveness of the techniques, as well as the friendliness and perceived level of security from the user's perspective.

The effectiveness was gauged by means of a practical trial, using specially designed profiling and authentication software to present the various techniques to a series of participants. Opinions relating to the friendliness and security of the methods were then obtained using a written questionnaire – completed by participants after they had participated in an authentication phase. The design of the experimental tools and the follow-up questionnaire are described in the subsections that follow.

#### **4.2.1 The Profiler**

The Profiler required participants to identify themselves and then provide appropriate responses for each of the methods under test. The profiling procedure for each of the methods is summarised below.

- Passwords and PINs. The implementation of these methods was fairly standard, with each participant being asked to supply a 4 digit PIN and a password of at least 8 characters. Participants were requested not to select a password or PIN that they already used on other systems, as the aim of the exercise was to assess their ability to recall new details, and thereby put these more familiar methods on an equal footing with the other techniques when it came to assessing ease of information recall. Nonetheless, as later results will indicate, some participants did not follow this guideline.
- Cognitive questions. Participants were asked to provide answers to a series of twenty questions, each requiring factual or opinion-based answers. The

questions requested information that was personal to the participant, and would therefore be difficult for a potential masquerader to guess in an operational scenario. The questions used are listed in Table 4.1.

|                                                          |
|----------------------------------------------------------|
| What is your mother's maiden name?                       |
| Where were you born?                                     |
| What is your favourite colour?                           |
| What was the name of your best friend at school?         |
| What is your favourite music?                            |
| What is your favourite food?                             |
| What was the name of your first pet?                     |
| Which primary school did you go to?                      |
| What is your favourite sport?                            |
| Where was your first house?                              |
| What make was your family's first car?                   |
| How old were you when you had your first kiss?           |
| What is your favourite film?                             |
| Where was the first place you remember going on holiday? |
| What was your favourite subject at school?               |
| What is the most important part of your body?            |
| What is your favourite type of animal?                   |
| What is the name of your favourite relation?             |
| How many cousins do you have?                            |
| What is your favourite shape?                            |

Table 4.1 - Cognitive questions

Even in cases where the participants might not have had a genuine answer (e.g. they may never have had a pet), it was expected that they would still be able to provide a response that could later be reproduced if prompted to answer that question.

- Associative questions. Participants were then asked to provide word association based responses to a set of twenty keywords. The keywords are listed in Table 4.2, and were carefully chosen to ensure that a number of

different responses were theoretically possible in each case. For example, for the associative word “seven”, responses might include “wonders”, “dwarves”, “sins” or “days”.

|        |       |          |          |        |
|--------|-------|----------|----------|--------|
| Blue   | House | Table    | Computer | Friend |
| Peace  | Glass | Marriage | Sea      | Love   |
| Cat    | Music | Fire     | Seven    | Video  |
| Father | Food  | Remote   | Fast     | Door   |

Table 4.2 - Associative keywords

- **ImagePIN.** The user had to select five images from a number of icons, by clicking on them with the mouse. Later authentication would work by the user reselecting the same images in the correct sequence (images are shown in Figure 4.1). Limiting the selection to five images meant that the resulting ImagePIN would not be considered as resilient to brute force attack as the 6-8 character passwords that are typically recommended. However, when viewed as an alternative to a traditional 4-digit PIN, as used with ATM cards and such like, the concept was considered to offer some useful potential.

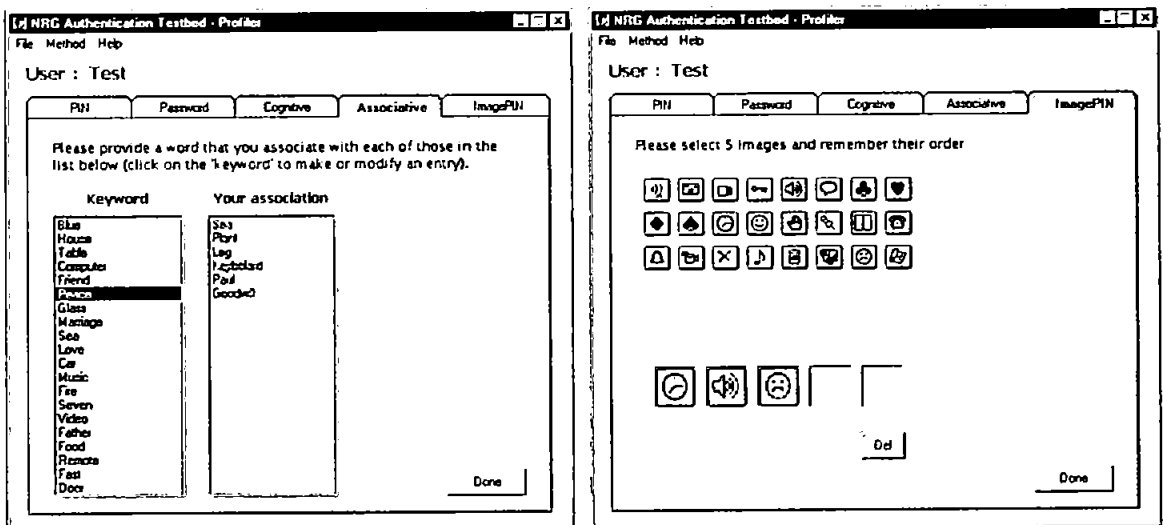


Figure 4.1 - Profiler system (showing associative questions and ImagePIN screens)

After the profile had been created, a short training exercise was performed using the second program, the Authenticator, in order to familiarise the users with how the later authentication test would work. After this, it was up to the participants to attempt to remember the details they had provided in order to perform the later authentication tests.

### 4.2.2 The Authenticator

The authentication tests took place one month after the initial profiling, with the aim of assessing whether the participants were able to adequately recall the information that they had previously provided during profiling and thereby authenticate themselves successfully. The interface of this system was very similar to that of the Profiler, and two aspects are illustrated in Figure 4.2.

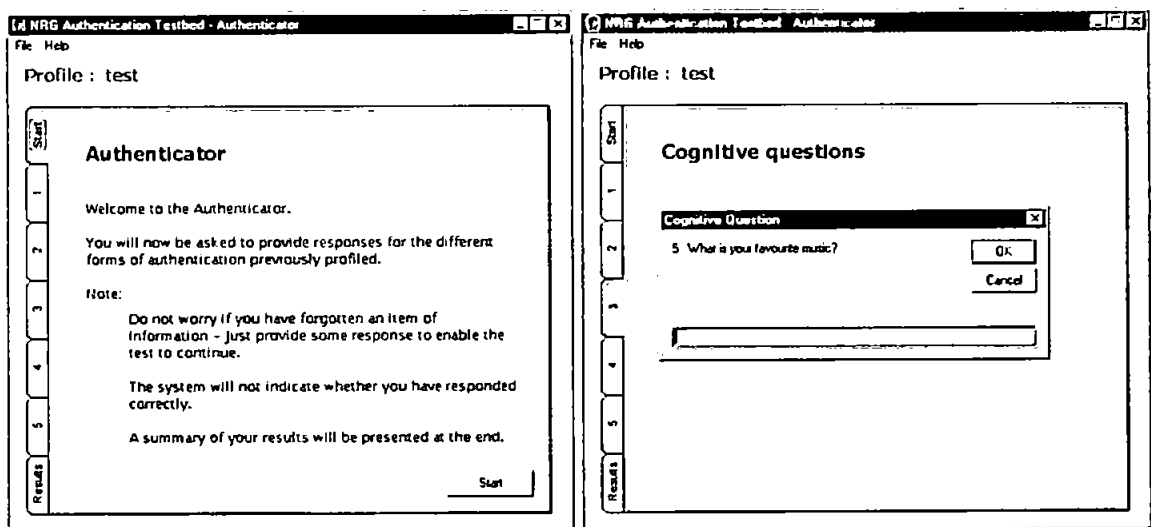


Figure 4.2 - Authenticator system (showing welcome and cognitive question screens)

In the case of the PIN, Password and ImagePIN methods, the participant was directly asked to provide the same information as originally profiled. For the cognitive and associative



methods, however, they were asked to answer five randomly selected questions out of the twenty that had been profiled in each case. This was considered to represent a good simulation of how such question and answer authentication techniques would be implemented in practice.

### **4.2.3 Participant questionnaire**

Following the authentication test, all the participants were asked to complete a questionnaire, in order to determine their regular exposure to user authentication methods in other contexts and to assess their views about the different methods under trial. The key information collected from the participants was the ranking of the trialed methods according to the perceived user friendliness, level of security, and overall preference (although several other questions were also asked).

A total of 27 participants were involved in the profiling and subsequent authentication testing, and the results of the study are described in the next section. While the number of participants was small, this did allow for baseline comparisons to be made between the different authentication techniques.

### **4.2.4 Experimental Results**

The results presented here consider the effectiveness of the techniques that were observed in the practical trial, as well as the participant's subsequent opinions in relation to the methods. It should be noted that, in the discussions and graphs that follow, the percentage figures have been rounded to whole numbers.

The practical evaluation began by examining the participant's performance in relation to the password and PIN methods. The results indicated that 70% of the participants had succeeded in authenticating themselves using passwords, and a similar proportion (67%) were successful using the PIN based method. Although these results initially appear very encouraging from the perspective of the participants being able to accurately recall the details after an absence of a month, the results of the accompanying survey revealed that a significant number of people had not followed the request to use different passwords and PINs than the ones normally used in other applications. In fact, only 56% used different passwords and 41% used different PINs. Within these subgroups, the authentication success was markedly lower - 53% of them succeeded in the password test and only 36% in the PIN version. By contrast, within the subgroups that used the same details as in other systems, 92% of them succeeded with passwords and 87% succeeded with PINs, so these figures can be considered to have artificially inflated the overall results.

In the cognitive and associative question tests, the participants were presented with a random selection of five questions out of the twenty that they were profiled for. Authentication was judged to be successful if all five questions were answered correctly. With the cognitive questions, a success rate of 59% was observed, whilst a number of further participants did succeed in answering a proportion of the questions presented to them. The distribution of correct answers in the cognitive test is shown in Figure 4.3.

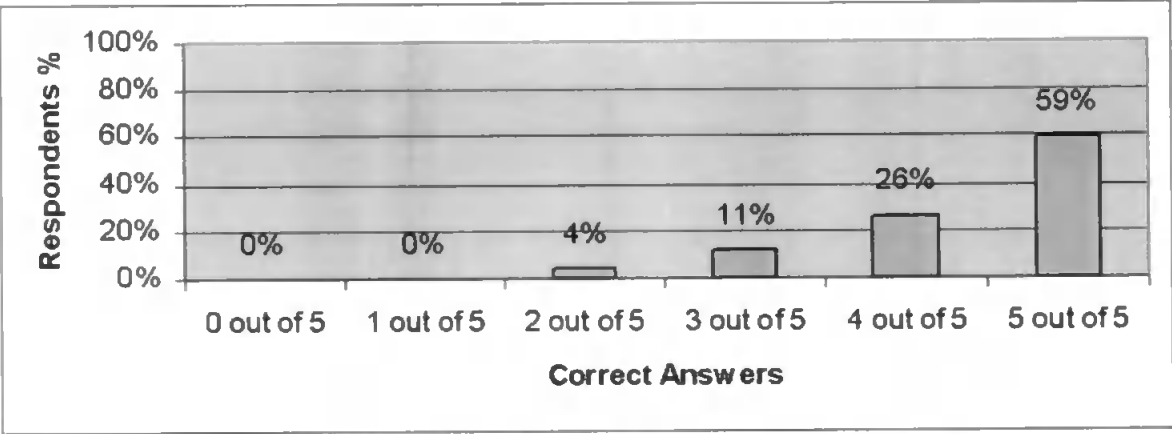


Figure 4.3 - Distribution of correct answers in cognitive questions

With the associative questions, the success rate was significantly lower. Only 4% (equivalent to one person) managed to correctly answer all five questions and the distribution of correct answers across five random questions is shown in Figure 4.4.

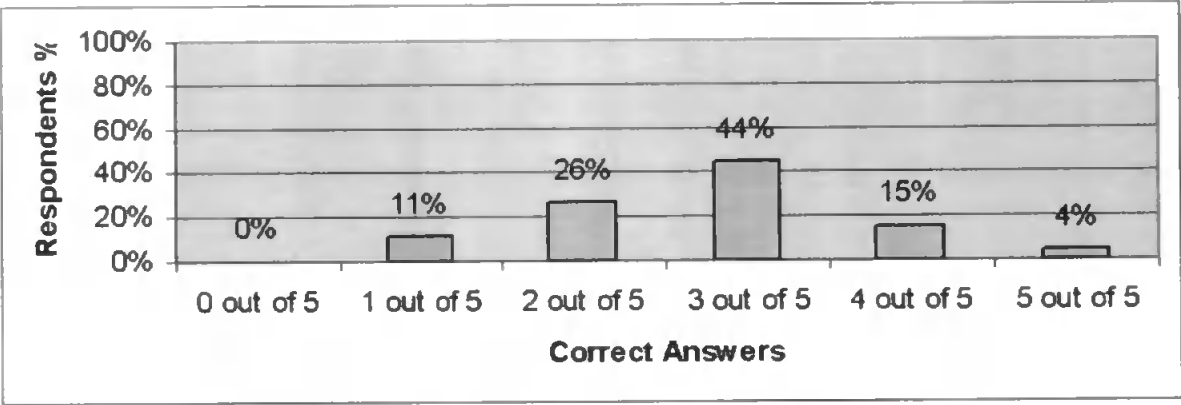


Figure 4.4 - Distribution of correct answers in associative questions

These results suggest that the associative question method is extremely problematic in relation to the correct recall of the information, and that participants are inconsistent in the words that they most readily associate with the keyword prompts. A further problem observed in the results of this study was that many participants chose the same associations for certain keywords, suggesting that the method could be easily targeted for masquerade attacks if used in practice. Table 4.3 summarises the cases in which the same associations were chosen for each keyword. The highest frequency of duplication was 44%, in which

respondents had chosen the word “control” as the associative response to the keyword “remote”.

| Keyword  | Frequent word associations           |
|----------|--------------------------------------|
| Blue     | Sky (41%), Sea (15%)                 |
| House    | Big (15%)                            |
| Table    | Food (22%)                           |
| Computer | Work (11%), Game (7%), Internet (7%) |
| Peace    | War (15%)                            |
| Glass    | Wine( 22%), Broken (11%)             |
| Sea      | Blue (11%)                           |
| Love     | Hate (11%), Marriage (7%)            |
| Music    | Rock (15%), Dance (7%)               |
| Fire     | Red (11%), Alarm (11%), Engine (7%)  |
| Seven    | Film (15%), Seven (7%), Days (7%)    |
| Video    | Games (11%), Movie (11%), Tape (7%)  |
| Father   | Mother (19%), Names (15%)            |
| Remote   | Control (44%)                        |
| Fast     | Food (22%), Car (19%)                |
| Door     | Key (11%), Open (11%), Closed (7%)   |

Table 4.3 - High frequency associative responses

For the final technique, the ImagePIN, the participants had to recall their graphical PIN by reselecting the original icons in the correct order, with 63% being successfully authenticated. Even though the implementation of the method offered the participants the opportunity to somewhat undermine the security by selecting the same icon five times, only two participants actually did this.

Figure 4.5 summarises the overall results of the authentication tests, indicating the percentage of respondents who would have been successfully authenticated using each of the methods.

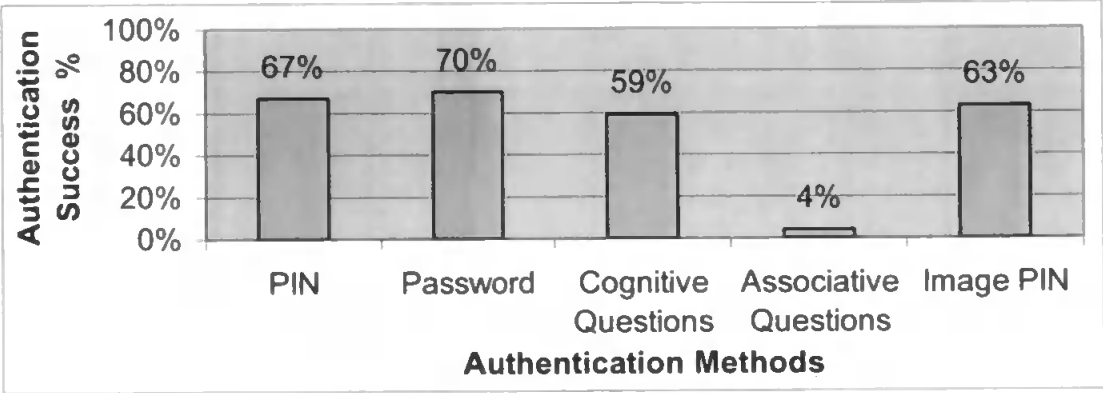


Figure 4.5 - Authentication methods success

Having experienced the techniques and witnessed their own performance, the participants were asked to rate the approaches on the basis of user-friendliness, security, and overall preference.

In terms of user-friendliness, participants were asked to assess the methods on a five-point scale, progressing from ‘easy’ to ‘hard’. The best outright indicator of preference in this case was where methods were ranked as ‘easy’. In this context, passwords were ranked first, receiving 48%, followed by the PIN method with 44%. The third position was shared by the cognitive question and ImagePIN methods, with 22% respectively. Last was the associative method with only 4%. Taking a wider view, and considering the total percentages for which methods were rated ‘medium’ or above, the password was still favourite, with 96%, followed by the PIN with 93%, cognitive questions with 81%, the ImagePIN with 59%, and associative questions with 48%. Looking from this viewpoint serves to place some separation between the cognitive and ImagePIN methods, and shows that more people tended to express concern over the friendliness of the latter technique. The full results are presented in Figure 4.6.

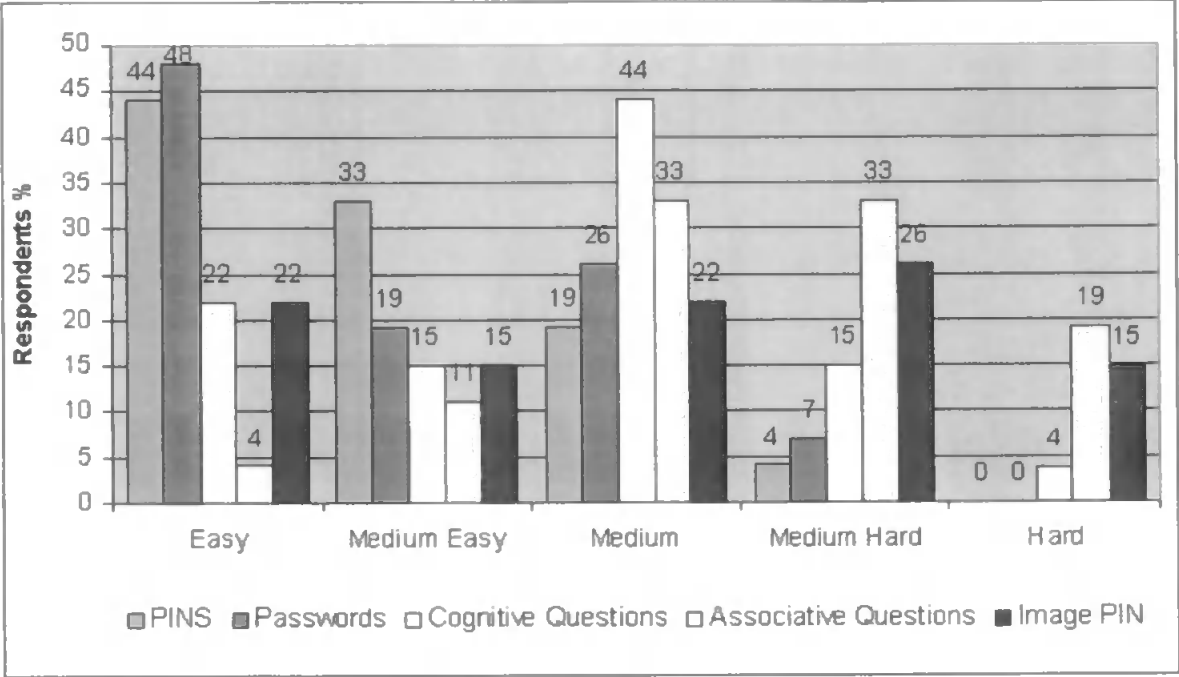


Figure 4.6 - Perceived user-friendliness

The second ranking addressed the perceived level of security. In this case, the password still fared well, with a combined total of 78% rating it to offer a ‘medium’ to ‘high’ level of protection. In this instance however, the popularity was also equalled by the cognitive and ImagePIN methods (and it can be noted that both of these methods actually exceed the results for passwords if only the ‘high’ and ‘medium high’ ratings are considered). Meanwhile, the PIN method attained 53%, and the associative approach was again ranked lowest, with 45% ranking it in the ‘medium’ to ‘high’ range. Figure 4.7 presents the perceived level of security for each authentication method.

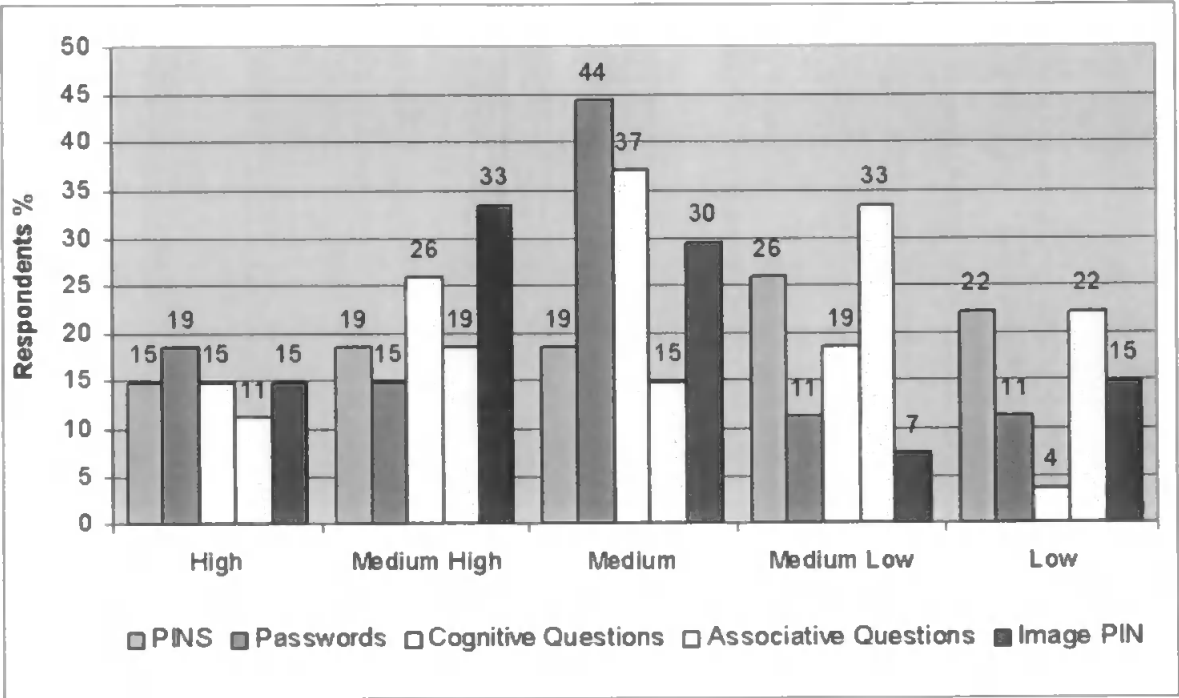


Figure 4.7 - Perceived security

The final question asked the participants to rank the methods according to their overall preference. The password method was again the most preferred form of authentication, with 44%, as shown in Figure 4.8. In second place is the PIN method with 22%, and third is the ImagePIN method with 19%. It is, therefore, demonstrable that the more traditional and familiar methods of authentication are still the most readily accepted. However, if the rationale behind the alternative methods is accepted (i.e. that passwords and PINs are open to compromise), then it is relevant to give further consideration to the results and responses in the other categories. This is not to suggest that the alternatives are themselves incapable of compromise – they will still be bound by the limitations of the implementation and the behaviour of the users.

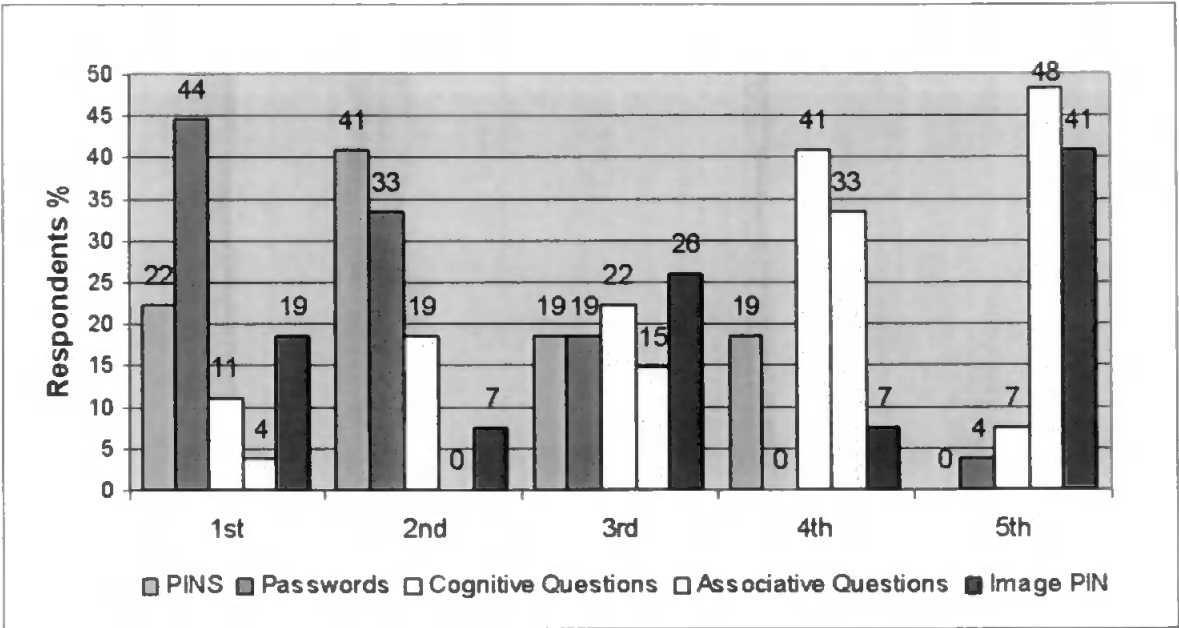


Figure 4.8 - Overall preference of trialled methods

4.2.5 Discussion

Although people clearly prefer passwords and PINs, the other results obtained continue to suggest concerns about the level of security they actually provide. For example, analysis showed that 48% of the participants selected passwords that might be easily guessed or cracked (e.g. based upon dictionary words, variations of their name, or foreign words written in English characters). Only 38% of participants used an alphanumeric combination, and fewer still (4%) introduced other symbols into their passwords. These results increase the attractiveness of the other methods, which may be less vulnerable to such unintentional compromise.

The participant’s performance in relation to the cognitive questions was relatively strong, with 59% achieving successful authentication (interestingly, a previous study by Haga and Zviran (1991) reported better results, 74% success, for a broadly similar set of cognitive



questions). Further points noted about the cognitive technique were the relatively time consuming nature of the profiling phase, in which the participants had to provide answers for all 20 questions. In addition, several participants expressed concern about the nature of the information that was requested, and were reluctant to provide genuine answers to the questions during the trial for fear that the information might be accidentally divulged. Particularly notable questions in this respect were in relation to mother's maiden name (a commonly used identity verification question in other contexts, such as bank accounts), place of birth, and age of first kiss. Overall, however, this method was ranked relatively high in terms of perceived user-friendliness and security.

The associative approach proved to be weak as an authentication method, with the performance of the participants (4% success) suggesting that it cannot deliver an adequate level of effectiveness. It is considered that this poor performance can in part be explained by the fact that users still have to remember potentially abstract information (as opposed to the more recognition-oriented approaches of cognitive questions), placing more or less the same demand on their memory as the password method. In addition, the results raise questions over the level of security that the approach would provide – the fact that many participants chose the same word associations suggests that the method would be vulnerable to attackers attempting to guess the likely associations. At the very least, this requires that more care must be taken in the selection of the keywords, to ensure that none of them have obvious first-choice answers. A previous study of the same basic method reported a far higher success rate, with an overall average 69% recall after a period of three months (Haga and Zviran 1991). It must be noted, however, that there was a significant difference in the experimental procedure in this case, as participants were asked to select their own keywords, as well as the appropriate associative responses.

The ImagePIN approach demonstrated positive results in the authentication phase, with 63% success, placing it very close to the results observed for passwords. This result is partially explained by the findings from previous surveys, which have shown that people tend to have less difficulty in recognising previously seen pictures than they do in recalling passwords or phrases from the memory (Bensinger, 2000 & Sasse et al., 2001). In addition to its practical effectiveness, the ImagePIN scored well in terms of user acceptance, which was considered to bode well for the rating that it might receive if users were given additional time to familiarise themselves with it. Another point worth noting is that the ImagePIN method as implemented for the study was rather crude, with a set of standard Windows icons having been used as the selection of available images. With more consideration given to the number and range of images available, it was considered likely that the perceived user friendliness of the approach could be further improved. Having said this, there was also a fairly high proportion of respondents who put it as their clear least favourite, whereas most of the other methods did not elicit such strong negative opinions.

Although some techniques suggested themselves as potential alternatives to standard passwords and PINs, it does not necessarily follow that they would make good replacement methods in all contexts. For example, the use of cognitive questions could potentially be too time consuming as a regular means of login authentication. The technique could, however, provide a good secondary level of authentication, which could be invoked in a number of scenarios (e.g. when a user tries to perform a sensitive activity, in response to a suspected masquerade attack, or simply at random intervals). Image based authentication techniques could be more easily implemented as an initial login technique, but their

applicability would be limited to systems that are able to offer sufficient graphical displays (e.g. mobile phones, Personal Digital Assistants and Automated Teller Machines).

With the exception of the associative approach, the practical effectiveness of the techniques was closely comparable. However, in terms of the overall preference, the known and familiar methods of passwords and PINs were, perhaps unsurprisingly, favoured. However, as indicated previously, if passwords and PINs were used in a secure manner (in accordance with guidelines) it is likely that the acceptance rates for these methods would decrease. If the previous arguments and evidence regarding the weaknesses of these methods are accepted, then it may be reassuring to consider that the cognitive and ImagePIN methods are already comparably effective from a user recall perspective, and given further training and exposure these methods may gain greater acceptance.

Although the initial results are encouraging the judgements relating to user-friendliness of the methods were based on a relatively brief level of exposure to the question and answer approaches and the ImagePIN method. The next section describes a longer-term trial in which participants used two of the alternative methods in day-to-day operations, in place of their normal passwords or PINs.

### **4.3 A Longer Term Study Of Alternative Methods**

While the initial trial had primarily assessed the effectiveness of the methods (i.e. the users' ability to recall the necessary information), the aim of the second trial was to

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evaluate the long-term user acceptance of the most promising of the alternate approaches, namely cognitive question and Image-PIN, with each technique being used in practice for several weeks (the associative question approach was not considered due to its weak performance in the first trial). For example, some users who initially found one or other of the new methods attractive might change their view in the longer term, whereas others who might have initially preferred passwords could come to prefer one of the alternatives once they became more familiar with it.

### 4.3.1 The Profiler

The software implementation of the profiler was based upon that used in the previous study (described in section 4.2.1) with some cosmetic changes to the interface of the ImagePIN approach. The original implementation had used relatively small, iconic images, which some participants had commented were not very meaningful, and so it was considered that using larger, more colourful images would aid their recall. The use of larger images has some drawbacks; most significantly it increases the potential for “shoulder-surfing” (i.e. the act of observing a user *over the shoulder*). It would, therefore, be necessary to introduce further safeguards to ensure the security of the chosen images in a typical office environment. It would also be necessary to consider the selection of images carefully in a live environment to ensure there is no link between an end-users lifestyle/hobbies and the available image library. The images used for this trial are pictured in Figure 4.9.



Figure 4.9 - New image sets used for ImagePIN

4.3.2 The Authenticator

Having collected the necessary information for each participant, the two authentication phases worked in the same manner as the first trial (pictured in Figure 4.10). Following each login attempt, the program logged the user’s results to a file. This enabled the research team to track the number of times that participants actually used the system, and how well they performed.

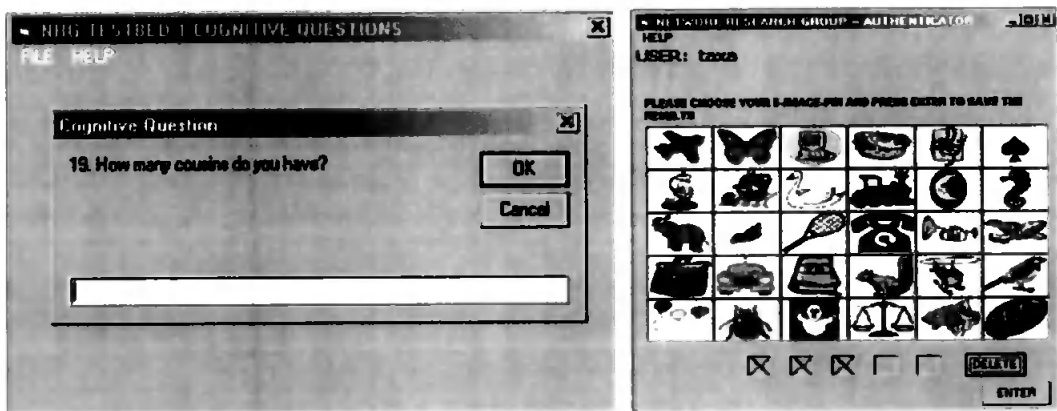


Figure 4.10 - Authenticator programs for cognitive questions and ImagePIN

For technical reasons (relating to the difficulty in interacting with the underlying security of Windows NT) it was not possible to replace the actual login authentication mechanism at the system level. However, in order to encourage users to make regular use of the

mechanisms on trial, the execution of the authenticator program was added as a scheduled task on participating systems. This ensured that the program would run automatically and remind the user to participate. However, in order to ensure that the program did not become unnecessarily intrusive (e.g. interrupting the user in the middle of important work), there was nothing to prevent users from terminating the program without actually entering any information. It is possible that some users may have chosen to close the program rather than respond to a specific, inconvenient, authentication challenge; however, the benefits of allowing users to terminate an inconvenient challenge in this trial were considered to outweigh the drawbacks of alienating test subjects.

Following the authentication trial periods, the acceptability and robustness of the techniques was assessed by means of a questionnaire. Key points of information collected included indications of:

- the perceived user friendliness of the techniques;
- the perceived security of the techniques;
- which, if any, of the trialed techniques could replace existing ones.

The trials were conducted for a total of ten weeks, split equally between the two alternative methods. 19 participants took part in the first stage, but unfortunately one user was not able to provide responses to the second stage and the subsequent questionnaire. The participants were primarily male post-graduate research students, in the 25-30 year age group. Although this represented a fairly limited sample from which to draw definitive conclusions about the methods, it was considered to provide a suitable basis for determining general results to accompany those from the initial study. In addition, the fact

that all participants came from a computing background meant that they were well-versed in the use of the traditional authentication mechanisms against which they would be asked to contrast the new approaches.

### **4.3.3 Experimental Results**

Despite concerns, it was discovered that each of the participants made a suitable degree of use of each approach (rather than simply choosing to close the authenticator application), with the cognitive question method being attempted an average 25 times per user, and the ImagePIN being used an average of 21 times per user. These figures correspond to approximately one use per participant per day, and are considered to be a sufficient basis for the participants to offer more informed opinions about the suitability of the methods as they would have had a similar level of exposure to the new techniques as currently experienced with typical username/password authentication.

Before considering the opinions, it is relevant to consider how effective the methods proved to be from an authentication perspective. In the cognitive question trial, the criterion for successful authentication was to correctly answer all five of the questions asked randomly by the program. The results indicated that 64% of the participants had succeeded to authenticate themselves using the cognitive question method. This was actually a slight improvement on the effectiveness observed in the original study, in which the cognitive question approach scored 59%. Nonetheless, the results still showed that some users had problems in memorising the required information, even though it was related to personal details. Figure 4.11 shows how the distribution of correct answers broke down across the sessions. Unexpectedly, it was founded that factual questions were

the ones that participants often answered wrongly. For example, questions 2, 8, 10, 12, and 19 were mostly answered incorrectly (refer to Table 4.1). A possible reason could have been the case sensitivity of the program; for example, some people may have entered words in upper case, but then entered them in lower case during authentication and were rejected. A further explanation could be the potential for variation in answering questions, for example, the question “What is your favourite music?” could be answered with a group name, genre, track or artist.

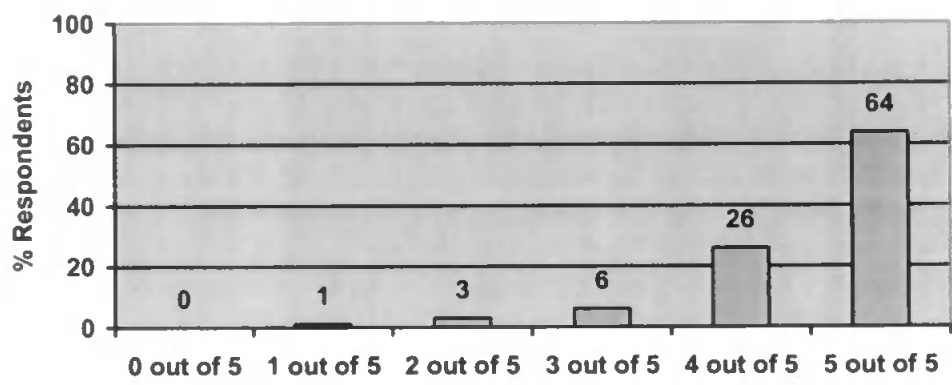


Figure 4.11 - Distribution of correct answers for the cognitive questions method

When considering the results for the ImagePIN, the criterion for successful authentication was the correct recall of the images in the same order they were selected in the profiling stage. The results, shown in Figure 4.12, indicated that 84% of the participants had succeeded in authenticating themselves.



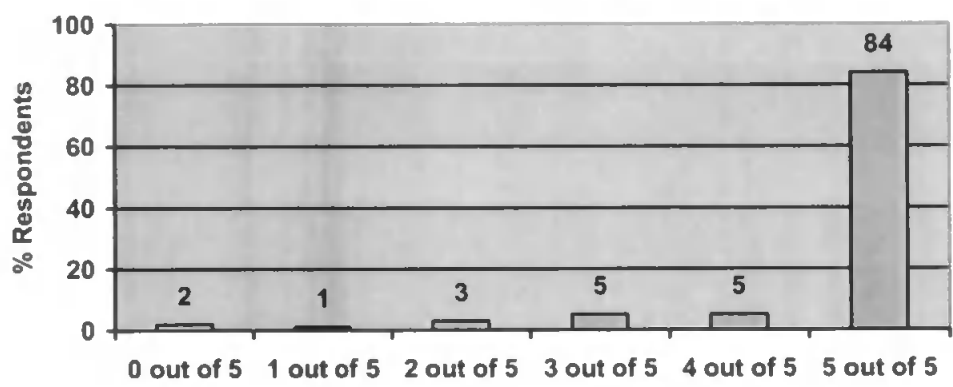


Figure 4.12 - Distribution of correct answers for the ImagePIN method

It can be noted that the participants’ overall performance was again notably better than in the original study (84% versus the previous ImagePIN result of 63%). One reason for the improved result (for both this method and the cognitive questions) could have been that the participants made use of the methods very soon after creating the profile, whereas in the first study they had been forced to wait a month (in order to evaluate their recall of the information). However, another contributing factor to the high success of the ImagePIN was that two thirds of the participants had chosen potentially weak sequences. Examples here included a sequential line of images, in the same horizontal row or vertical column, or selecting five instances of the same image (approaches which clearly made the information easier to remember). Possible solutions to this would be to prevent selection of duplicates, and to reposition the images each time the program runs. However, there would be a strong possibility of this reducing the success rate.

Following the trial period, the eighteen remaining participants were asked to provide answers to the evaluation questions. They were firstly required to indicate whether they believed that either of the new techniques could replace the existing ones (i.e. passwords or PINs) for login authentication. The responses revealed that 56% of users supported this

idea. However, as Figure 4.13 shows, the two techniques did not meet with equal approval, with the cognitive questions approach being clearly preferred.

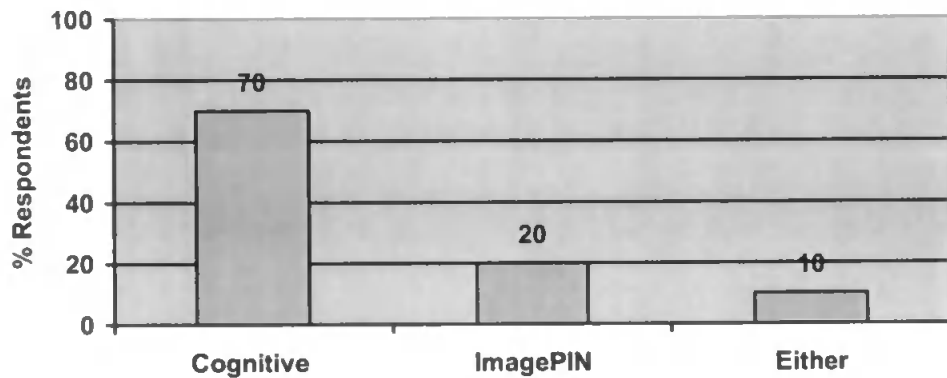


Figure 4.13 - User preference for replacement method

Continuing the evaluation, participants were asked to assess the techniques in terms of their ease of use, using a four-point scale, progressing from “Very easy” to “Very hard”. The results are shown in Figure 4.14, conveying the impression that the overall difficulty associated with the cognitive questions approach is less than that for the ImagePIN (with none of the participants rating the cognitive approach as ‘very hard’). By contrast, the ImagePIN results suggest that the method is more likely to elicit strong feelings from the users, with many more responses focusing at the two extremes of the scale.

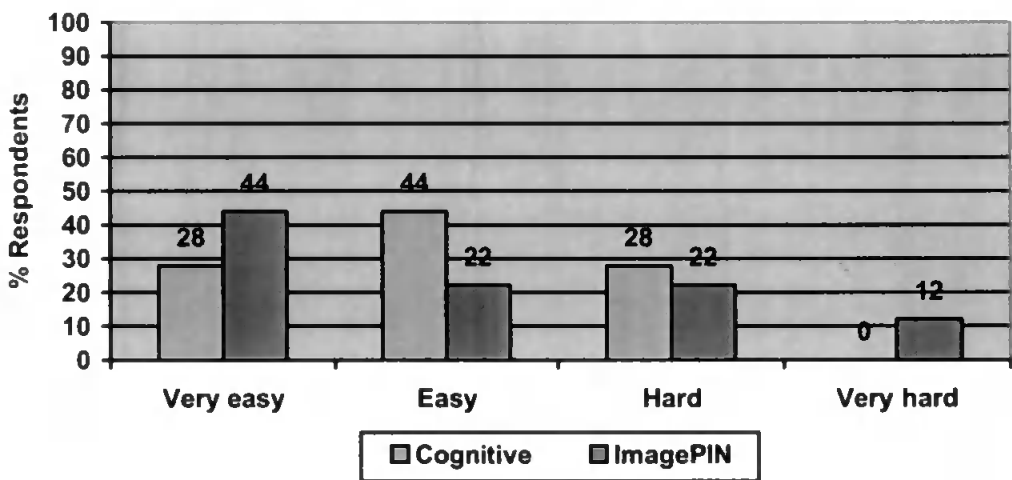


Figure 4.14 - User ratings for perceived ease of use

Given that one of the principal problems with traditional passwords and PINs is that people often find them hard to remember, it was relevant to consider this aspect with the new methods. When asked if they had difficulty in remembering the required information, the participants responded as shown in Figure 4.15. This indicates that users have found the cognitive questions most difficult, contrasting with the earlier findings from Figure 4.13, which indicated that 70% preferred this method. It should be noted that the results in Figure 4.15 are based on the full population of participants, whereas Figure 4.13 was only based upon 56% of them as participants were only asked to answer *if* they believed the existing password/PIN techniques could be replaced.

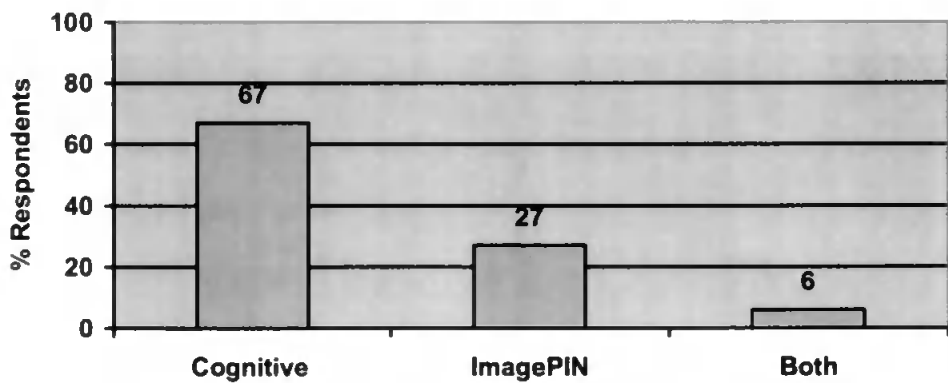


Figure 4.15 - Perceived difficulty to remember the required information

Another important factor was the resulting security that the replacement techniques were perceived to provide. The reason for considering the replacement of existing passwords and PINs is that they have been found to be vulnerable to compromise by legitimate users, and to attack by impostors. In order to evaluate the perceived security of the selected methods, users were asked to rate them on a four point scale, progressing from “Very easy” to “Very hard”, when considering the possibility of an impostor being able to guess the required information. The distribution of the responses is shown in Figure 4.16.

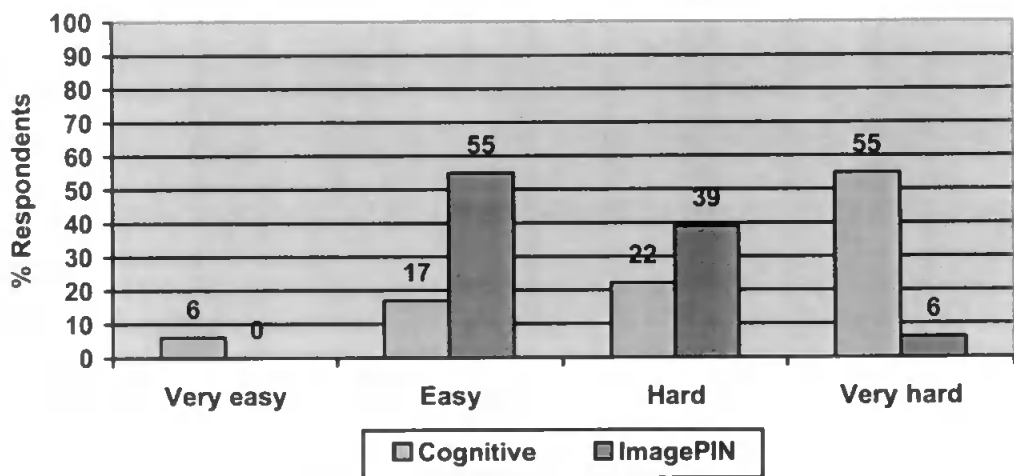


Figure 4.16 - User ratings for ease with which methods could be broken

The results show that 55% of the participants believed the ImagePIN to be the easier to guess which contrasts with the earlier findings (Figure 4.7) where 47% of the participants perceived ImagePIN's to have a high/medium-high level of security. Their feedback suggested that it would be easy for an impostor to find the appropriate sequence by sitting behind the user, or simply by guessing possible sequences. The latter observation was possibly reflective of the fact that many users had chosen weak sequences, and considered that other people would do likewise. A larger variation was found in the earlier results for cognitive questions where 55% perceived a low/medium-low level of security compared

with 77% who later considered the method to be hard/very-hard to be bypassed. This perhaps indicates a change of opinion following prolonged exposure to the method.

In order to further, evaluate the Image-PIN method participants were asked to assess the difficulty to remember the 5-images selected from the image grid provided. The participants were asked to assess the method on a four-point scale, progressing from “Very easy” to “Very hard”. The results are shown in Figure 4.17. While over 60% of users considered the approach to be easy/very easy, a significant number considered the approach to be hard/very hard. This approach may be viable as an authentication technique, however, more work must be done to make this method more user-friendly.

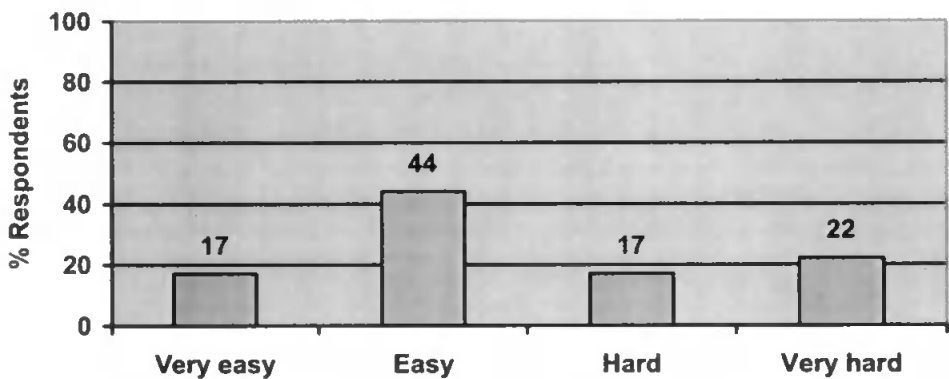


Figure 4.17 - Perceived ease of remembering a 5-image sequence

The final question asked the participants if they would be prepared to use the methods for login authentication. Findings indicated that 56% of users would be prepared to use the cognitive questions method for login, and 39% of users for the Image-PIN method respectively (Figure 4.18).

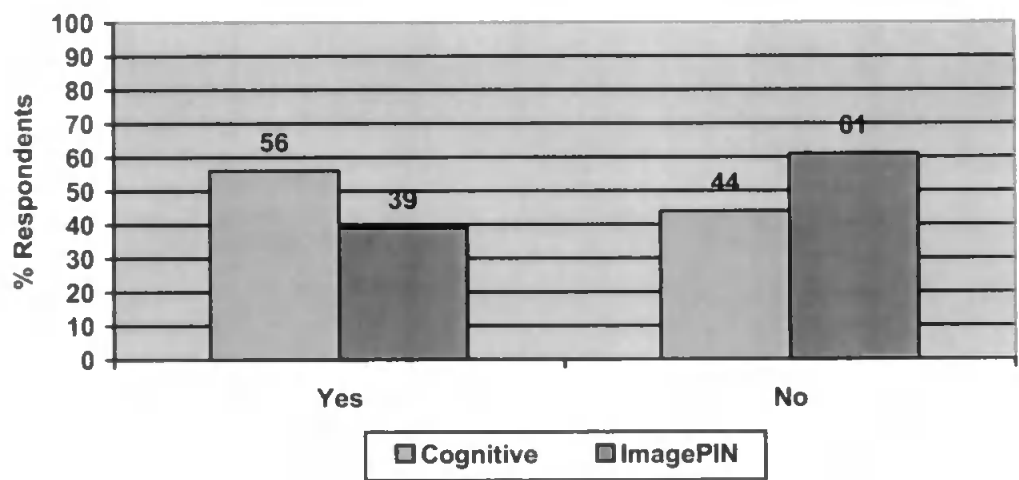


Figure 4.18 - Overall user acceptance of the techniques

Most of the users that rejected the cognitive question method for login authentication did so on the basis that the method was time consuming and that they had problems relating to the entry of the data. By contrast, most of the users that rejected the ImagePIN method expressed concerns regarding the interface design and the selection of the images, as well as security implications. With such a high level of user rejection for the evaluated techniques, it is clear that further work is required to improve the user perception/practical issues as well as addressing the technical aspects. It can be observed that for the user community as a whole, neither technique represents the natural successor to passwords. However, the results do suggest that they offer some potential in some contexts.

4.3.4 Discussion

The participant’s comments about the methods highlighted some further interesting points that were not apparent from the statistics alone. In some cases, these opinions raised further legitimate questions about the viability of the techniques, whereas in others they

flagged issues that would be unlikely to be genuine considerations in practice. Nonetheless, the fact that such comments were made even within a small sample population suggests that similar misconceptions could also be reflected within a wider user community.

In the case of the cognitive questions method, individual opinions suggested that it would be easy for impostors to acquire the required information by social engineering (e.g. having brief conversations with the user, or friends of the user in order to find answers to the questions). Set against this, however, is the fact that an impostor must know all the answers in order to guarantee successful access to the system, because the questions are presented randomly to the user. In addition, even if the attacker found the answers, they must also know how they were typed in the profile stage (e.g. for the question “How many cousins do you have?”, did a user with three cousins enter their answer as “Three”, “three”, or “3”).

A problematic aspect of the cognitive question approach was that it was considered to be too time consuming, ruling it out for login authentication, and suggesting that it should only be used where higher security requirements justified the effort. Another valid point was that basing the authentication on factual information meant that answers would be impossible to change if the method was compromised (i.e. users cannot simply change their answer to a question such as “What is your mother’s maiden name?” in the same way that they could change a password). This would mean that the questions themselves would have to change as well. As such, investigation of how well users are able to adapt to changing questions would be another valid avenue of further research arising from this study.

In the context of the ImagePIN, there were several comments about the user interface. Participants suggested that the method should have more image grids or different images for selection, as well as better images, and the option to choose individual images in order to complete the grid. Addressing these factors would have the potential to improve the level of user acceptance. Further potential refinements could consider the random positioning of images (as previously mentioned), or the use of a static subset of images from a much larger collection so that users could select their preferred images (i.e. the user would select 20 images from a large collection and then select their ImagePIN from the subset – for authentication, only the subset would be presented, this would allow a user to select similar images that are only distinct to them). If a much larger set of images were available, authentication could be conducted with a randomly selected range of images (i.e. 4 or 5 valid images with a number of random invalid images). Another refinement could involve selecting each image individually from a random group of images. This would increase the number of invalid images for each part of a 4 or 5 image PIN and thus increase the number of combinations (e.g. a 5x5 grid of images shown five times would give a total of nearly ten million combinations). However, randomising the images in this manner could adversely affect the usability and acceptance of the technique as there would be an increased delay while the user identified the position of the image(s). A potential solution to this would be to reduce the number of images presented (with a subsequent impact on the level of security of the method).

Although many participants appeared to consider the ImagePIN vulnerable to compromise by guesswork, it is worth noting that the probability of a properly selected sequence being broken by this means is 0.000000041. However, the clear problem from practical experience was that many users did not select appropriate sequences, leading to the



conclusion that the implementation of such a technique could be a high risk for security-unaware users. As with all access control systems, if the authentication mechanism is too difficult or inconvenient to use, end-users will find ways to subvert the system.

Given the inherent difficulties in the above methods (spelling mistakes, forgetting images etc.), all of the proposed methods could suffer from some of the same issues that make passwords weak, namely that users will forget their login details and may have to write them down. Preventing users from doing this may increase the loading on administrators with users requesting ImagePINs to be reset, or answers to be retrieved. To resolve this, users need education in appropriate selection of their authentication responses.

## **4.4 Conclusions**

The two trials described in this chapter have provided interesting results regarding the use of alternative secret-based authentication techniques. The first trial suggested that longer exposure to the methods would allow a more accurate impression of user acceptance to be gained. The second study demonstrated that longer exposure to the methods can improve both acceptance and the rate of successful authentication, suggesting that each of the techniques offers some potential as a replacement or supplementary authentication mechanism. However, none of the evaluated techniques appeared to represent an ideal solution that could consequently be used to replace traditional passwords and PINs for all users in all contexts. In addition, full-scale implementation of the techniques could still be hampered by the ways that people can potentially misuse them.

In parallel with considering alternative authentication methods, there is also a need for improved user education, both in terms of selecting appropriate information to act as their authentication secret, and also in appreciating the level of security offered by different techniques. The solution to login authentication lies not just in technical implementations, but also in the way end-users interact with the measures employed.

The results of these trials suggest a number of further research projects that will be discussed in more detail in chapter 9.

Having evaluated these approaches, it is clear that software-based approaches are popular with users and could compare favourably with passwords if implemented properly. The results do, however, indicate that users still had difficulty in selecting both unique and non-predictable secret information. This again serves to reinforce the fact that users frequently undermine authentication systems through misuse (albeit often inadvertent). In order to build on the use of software-based techniques, whilst moving away from secret-based methods, the next chapter presents the use of keystroke analysis as an alternative authentication mechanism to the traditional username/password, before considering a similar trial to evaluate the use of keystroke analysis in chapter 6.

# **Chapter 5**

## ***Approaches to Keystroke Analysis***

## **5.1 Introduction**

Chapter 3 identified the need for a method of transparent continuous user authentication, with the respondents indicating a preference for a method based upon keystroke analysis. Before looking at the keystroke analysis methods, alternative software-based authentication techniques were evaluated and described in the previous chapter – this chapter determined that alternative secret-based authentication has potential but may best be applied as a response mechanism for specific authentication challenges. This chapter summarises the potential approaches to keystroke analysis, presents a novel method based on application-specific user profiling and considers the use of multiple metrics to create a composite supervision system.

The concept of keystroke analysis is by no means a recent development. Previous work, published in 1980, first identified the profiling of key-presses as a potential method of user authentication (Gaines et al, 1980). Since then a number of research projects have been conducted to evaluate different methods of data gathering (using a range of operating systems and considering a variety of metrics) and post-processing techniques (ranging from purely statistical to AI/neural network approaches). Later in this chapter these projects are summarised and compared.

Before looking at the results of previous work in this area, it is first necessary to determine which characteristics of typing are viable for profiling and authenticating against. Previous studies have identified a selection of data acquisition techniques and typing metrics upon

which keystroke analysis can be based. The following section summarises the basic methods and metrics that can be used.

## 5.2 Metrics

There are a variety of possible keystroke metrics that can be profiled as the basis for subsequent comparison. The main methods are based on timings between consecutive keystrokes, and consider either the latency between two consecutive keypresses (digraphs) or three consecutive keypresses (trigraphs). Other possibilities include the mean typing and error rates.

- **Digraph latency** - Digraph latency is the metric that has traditionally been used for previous studies. This measures the delay between two consecutive keypress events that are produced during normal typing (e.g. when typing the word 'THE' two digraph timings can be generated - T-H and H-E). Given a suitable volume of digraph samples the character distribution of the English language will ensure that a range of commonly occurring digraphs will be generated that can subsequently be profiled. In most cases, some form of low and high pass filter is applied to remove extraneous data from the session/profile data (discussed in section 5.5.1).
- **Trigraph latency** - Trigraph latency extends the previous metric to consider the timing for three successive keystrokes (e.g. T-H-E). Spaces are usually ignored – e.g. the word THERE could generate three trigraph samples, T-H-E, H-E-R and E-R-E, with the final trigraph R-E-[space]

ignored. As with digraph latencies, the application of a low and high pass filter is usually required. It should be noted that the occurrence of trigraphs (and digraphs) would normally comply with the rules of English – i.e. T-H and T-H-E are likely to be the most commonly occurring. However, as new words (and in particular acronyms) are introduced these distributions may change. For example, the introduction of the world-wide-web has introduced the trigraph W-W-W that would have been unlikely to occur twenty years ago. It is probable that over time, the distribution of digraphs and trigraphs will change and as such, any system that relies upon these measures will also have to change (i.e. profiles will have to undergo periodic refinement).

- **Keyword latency** - Keyword latencies consider the overall latency for a complete word, or may consider the unique combinations of digraph/trigraphs in a word-specific context. The use of keyword latencies allows not only profiling of commonly occurring words, but also the ability to monitor words that could be interpreted as commands to the operating system or applications running on the system – i.e. a command with a high misuse risk (e.g. delete or format) could be specifically monitored or a specific function in an application (e.g. entering an application-specific command with a high risk consequence).
- **Keystroke duration** – Keystroke duration considers a different metric to that of the digraph and trigraph latencies. This approach considers the duration of each individual keypress (i.e. the time between the key-down

and key-up events for a single key as opposed to the latency between two/three key presses). While this approach is worthy of investigation, it does introduce significant limitations. 26 letters of the alphabet provide far fewer profile-able characteristics than digraphs – with a maximum of 676 ( $26 \times 26$ ) discernible values. The actual number of digraphs encountered in typed language is likely to be less than this as certain digraphs do not commonly occur (e.g. ZZ, QA). It is also likely that the keypress duration will be less variable than digraph latency as there would be no hand movement or changes between hands in the keypress duration – unlike the digraph latency.

- **Keystroke pressure** – Keystroke pressure relates to the level of pressure applied for each keypress. It is not possible to obtain pressure values from a standard computer keyboard, and as such the use of a customised keyboard specifically designed to produce pressure values in addition to the usual keypress would be required. While this approach may have some potential, the need for a modified keyboard makes this inappropriate for practical use.
- **Mean typing rate** – Whilst this may not be user specific, it may be possible to classify users into a generic category, according to their typing ability, which can then be used as an additional authentication method or potentially to set filter thresholds.

- **Mean error rate** – Finally, the mean error rate can be used to provide an indication of the competence of the user during normal typing. It might also be feasible to evaluate a users' typing errors – e.g. certain users may mistype the same word or words consistently. As with the mean typing rate, individuals could be classified according to their typing ability and hence evaluated based on their average typing accuracy.

While the final two metrics indicated above are unlikely to provide a suitably fine-grained classification of users for direct authentication judgements, they may be used to provide a more generic set of user categories that can contribute to a combined measure. The environment in which they are used will determine the usefulness of such non-specific metrics. For example, monitoring typing speed and error rate within a pool of touch-typists would be of little value, as there is unlikely to be any significant deviation between each user's profile.

### 5.3 Collection methods

In addition to the variety of metrics that can be recorded, there are also variations in the methods of data collection. The following list presents a number of ways in which user-typing patterns can be acquired and subsequently used for authentication purposes.

- **Static at login** – Static keystroke analysis authenticates a typing pattern based upon a known keyword, phrase or some other pre-determined text. The captured typing pattern is then compared against a profile previously



recorded during system enrolment. Static keystroke analysis is generally considered to be an initial login enhancement as it can supplement the traditional username/password login prompt, by checking the digraph latencies of the username and/or password components (i.e. authenticating the user on the basis of both what they typed and how they typed it).

- **Periodic dynamic** – Dynamic keystroke analysis authenticates a user on the basis of their typing during a logged in session. The captured session data is compared to an archived user profile to determine deviations. In a periodic configuration, the authentication judgement can be intermittent; either as part of a timed supervision, or, in response to a suspicious event or trigger. This method provides distinct advantages over the static approach. Firstly, it is not dependent upon the entry of specific text, and is able to perform authentication on the basis of any input. Another factor is the availability of data; in static keystroke analysis, the range of digraphs and frequency of their occurrence is likely to be significantly limited compared with a dynamic approach. Even an inexperienced typist is likely to produce sufficient digraph pairs to allow an authentication judgement to be derived. This is an important factor as it is necessary to have a large volume of keystroke data in order to generate a user profile.
- **Continuous dynamic** – Continuous keystroke analysis extends the data capturing to the entire duration of the logged in session. The continuous nature of the user monitoring offers significantly more data upon which to base the authentication judgement. With this method it is possible that an

impostor may be detected earlier in the session than under a periodically monitored implementation. On the downside, however, the additional processing required will add to the computational overhead of the supervision system.

- **Keyword-specific** – Keyword-specific keystroke analysis extends the continuous or periodic monitoring to consider the metrics related to specific keywords. This could be an extra measure incorporated into a monitoring system to detect potential misuse of sensitive commands. For example, under a DOS/Windows environment it may be appropriate to monitor the keystroke metrics of a user attempting to execute the `FORMAT` or `DELETE` commands. This could represent a significant enhancement, as a command with a high misuse consequence (e.g. `DEL *.*`) is unlikely to cause sufficient profile deviation when observed from a system-wide context, due to the limited selection of digraphs. By contrast, static analysis could be applied to specific keywords to obtain a higher confidence judgement.
- **Application-specific** – Application-specific keystroke analysis further extends the continuous or periodic monitoring. Using this technique, it may be possible to develop separate keystroke profiles for distinct applications. For example, a user may be profiled separately for their word processing application and email client as a user may type sporadically in response to emails while word processing generally has

prolonged periods of continuous typing. The potential of this new technique is discussed in more detail in section 5.7.2.

It should be noted that all of the above techniques and metrics could be implemented on a standard PC platform, without the need for special hardware (e.g. the only requirements are a PC and the ability to run the monitoring software). This offers a significant advantage over other alternative authentication and supervision techniques (discussed in Chapter 2), as a standard keyboard is present on almost all PC's. However, this approach is not without its drawbacks and thought must be given to the ethical and legal questions that may arise when proposing such close supervision of computer users.

## **5.4 Methods of implementation**

The actual methods of collecting and subsequently verifying user keystroke data vary depending on the operating system on which the collection is to take place and also upon the nature of the characteristics being monitored.

There are three potential methods to obtain keystroke data:

- Custom application – this method can be used to provide a custom front-end through which a user's typing patterns can be assessed programmatically or added to an existing application to provide context-sensitive analysis of user interaction. This could, for example, be used to demonstrate the concept of keystroke analysis by presenting the user with a user interface in which they

would be required to either type pre-determined text (e.g. a password) or allowed to type freely. Depending on the operating system, this may require substantial coding to obtain the necessary signals indicating the keypress events. This method is limited in its operation, as it will only monitor typed content within the specific application. As such, its use is restricted to enhancing security within an application or to act as a response to a security issue – i.e. to request the user to authenticate with a stronger confidence than password only.

- **Modification of operating system** – this method is considerably more involved than the previous approach as it requires an understanding of the underlying operating system. Using this approach it is possible to replace the login authentication presented under Microsoft Windows (by modifying the GINA.DLL that provides the graphical user interface for the login prompt as part of the Graphical Identification and Authentication services under Microsoft Windows). This process is applied in the Windows software product BioPassword described in chapter 2 and illustrated in Figure 5.1. This method has distinct advantages in that no specific user action is required in order to authenticate as the process of keystroke analysis is integrated into the traditional login prompt. As with the previous method, this approach is limited in its scope as it would only be activated on login (or when the terminal is locked or the screensaver deactivates – assuming such options are available and are enabled).

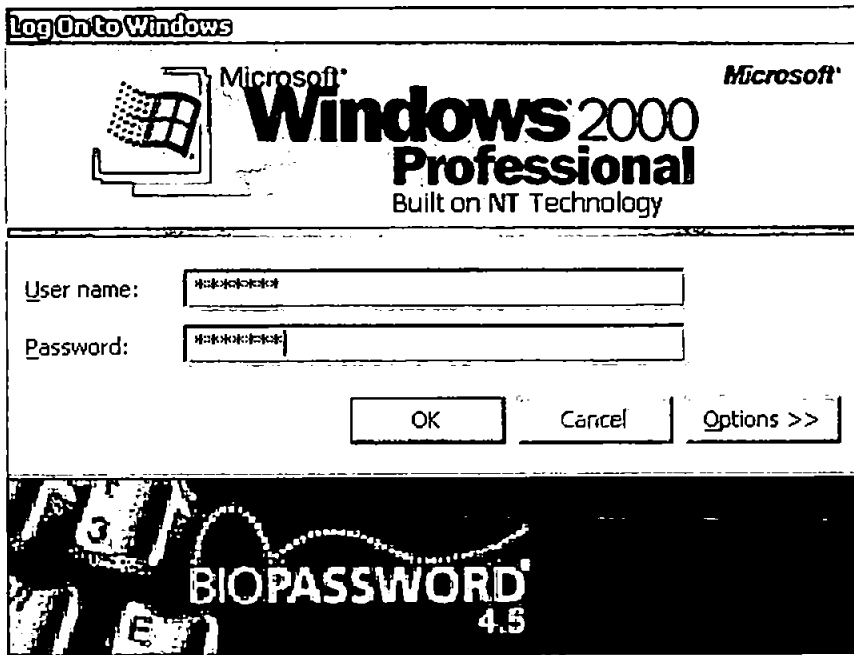


Figure 5.1 - Biopassword login screen

- Capturing keystroke data – this method uses a custom application to effectively *sniff* keystroke activity by intercepting keystroke messages (under Windows) or by redirecting pipes (under Unix/Linux). The appropriate software to enable logging of the keystrokes then processes these messages. This approach is considered the most flexible (and hence appropriate) of those outlined in this section because it can be implemented in a completely transparent manner. This approach will be discussed in more detail in chapter 6 where a prototype system is described.

## 5.5 Processing Keystroke Data

Once the keystrokes have been obtained (using one of the methods outlined in the previous section, it is necessary to filter the keystrokes (to remove low and high latencies) and to then perform post-processing to extract data on which to base a user profile.

### 5.5.1 Filtering

For most implementations, some form of low and high pass filter is required to remove extraneous samples from the session/profile data. Low pass filtering is important as it ensures that undesirable typing characteristics (e.g. stuck keys or repeated key-scans) are eliminated from the profile. The use of a high pass filter helps to ensure that excessively long digraph timings (which could be indicative of a distraction during typing) are also eliminated. The use of such filters could of course have negative side effects – i.e. an impostor or masquerador could attempt to bypass security (given appropriate knowledge of the system) by typing commands so slowly that the high pass filter would ignore the majority of keypresses. To remedy this, it would also be necessary to monitor the proportion of *filtered* digraphs to ensure that a number of consecutive incidents are flagged.

In addition to the filtering of low and high timings, intelligent filtering is usually needed (for all methods) to remove certain control keys (i.e. the function keys F1-F12, CTRL and ALT keys etc.) as these are unlikely to provide any meaningful contribution to the profiled samples.

### 5.5.2 Post processing and comparison

This section considers the issues of post-processing and comparison from a digraph-centric perspective. However, it should be noted that all the points raised are equally relevant to trigraph and keyword-based profiling.

Once the data is gathered it is necessary to process the raw keystroke samples to provide a comparative profile against which session data can be compared. The production of a profile is not an insignificant task. If the approach being taken is purely statistical, the data must first be cleaned to remove sample outliers that may affect the range of valid values for each profiled digraph/trigraph – to tighten the distribution for each profiled digraph (as described in the previous section). Once the data is cleaned, the profile is generated based on the valid data obtained from the user. One method (described in more detail in chapter 6) involves the production of a mean and standard deviation for each digraph recorded (although there are other statistical techniques employed by the studies described in the following section). Once a reference profile has been created, subsequent user data can be compared on a digraph-by-digraph basis against the reference profile, recording the deviation from the expected typing patterns. The output of such a comparison could be a simple count of accepted versus unaccepted digraphs, but could also consider the number of consecutive matched, unmatched, accepted and rejected samples (matched and unmatched refers to samples where a valid digraph profile does or does not exist – i.e. the user profile may not have a recorded entry for a specific digraph pair).

An alternative to the statistical approach is to use a neural network method. To use a neural network approach, the data is split into two parts. The first part of the data would be used to generate a profile – typically selecting the top  $n$  occurring digraphs for the user and then feeding each digraph timing through a neural network. Once the network is trained using the first data set, the second set can be used to verify and improve the network's performance. Finally, the data from other users can be fed through the same network to determine the false acceptance rate for the users' profile. The output of this method would

normally be a classification accuracy – i.e. the confidence that the sampled data matches the expected users' profile.

Both of these methods have been considered by a number of trials investigating the use of keystroke analysis utilising digraph samples (a selection are listed in Table 5.1). However, there are significant problems with the use of either method. A purely statistical approach relies upon sufficient data being available to allow a profile to be generated – if too little data is present, the accuracy of the profile will be jeopardised as the deviation for each profiled digraph could be very high (more samples are needed to make the high/low timings less significant). The neural network approach requires a reduced subset of digraphs (typically choosing the  $n$  most commonly occurring) as any increase in the number of inputs to the neural network (where one input is required for each profiled digraph) increases the complexity of the networks and the time taken to process the data. This results in a trade-off between reducing the number of inputs to speed up the data processing while ensuring enough data to accurately authenticate a user.

The neural network method, while limited by the volume of data collected in keystroke analysis, may be able to identify patterns in user profiles (i.e. identifying distinguishing digraphs for each user) that would be missed by a purely statistical approach. While not considered in the first trial described in chapter 6, the use of neural networks will be revisited in chapter 8.



## 5.6 Summary of previous work

The idea of using keyboard characteristics for authentication is not unique, and there have been a number of previous published studies in the area. To date, however, virtually all published studies have focussed upon static or context-independent dynamic analysis, using the inter-keystroke latency timing method. From the earliest studies in 1980 (Card et al & Gaines et al), the focus has been on the analysis of digraph latencies. Later studies, such as those by Joyce & Gupta (1990) and Mahar et al (1995) further enhanced the work, identifying additional statistical analysis methods that provided more reliable results.

In Legget et al. (1991), the concept of dynamic keystroke analysis was first proposed, with the introduction of a reference profile that could be used to monitor a live user session. Brown and Rogers (1993) also explored the idea of dynamic analysis, presenting preliminary results.

A summary of some of the main results from studies to date is presented in Table 5.1 below, which illustrates the effectiveness observed (in terms of false acceptance and false rejection errors), as well as the type of keystroke analysis technique employed (digraph/trigraph etc.) and the analysis approach taken (statistical or neural network).

As can be seen from Table 5.1 the range of results shows the inherent unreliability of the keystroke analysis approach – with large variations in both FAR and FRR rates. It can be observed that in almost all cases, the FAR rates have either been fixed at 0% (optimising the system under test to reject all known impostor activity) or have been less than 10% (less than 1 in 10 impostors would be authenticated by the keystroke analysis system).

However, with some experiments producing FAR rates in excess of 10% it is clear that the previous work in the area has still not entirely addressed the problem of false acceptance. As different organisations will have differing security requirements, there is no single FAR rate that will prove acceptable to all – while all organisations will aspire to 0% FAR, it is unlikely to be feasible due to the inverse relationship with the FRR rate (Figure 2.2) and the consequent affect on user attitudes and opinions when high rejection rates are encountered. Several studies have forcibly fixed the FAR to 0% by optimising the software to reject all impostor attempts during the experiment run. However, this can only be achieved at the expense of the false rejection rate. By fixing the FAR at 0%, the system has to be much more precise about accepting a login attempt – this results in an increased FRR.

| Authors                                                                       | Method                                                               | Participants                      | %FAR                                  | % FRR                                   |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------------------|---------------------------------------|-----------------------------------------|
| Umphress & Williams (1985)<br>Static                                          | Digraph<br>Statistical                                               | 17                                | 6%                                    | 12%                                     |
| Legget & Williams (1988)<br>Static                                            | Digraph<br>Statistical                                               | 17                                | 5%                                    | 5.5%                                    |
| Joyce & Gupta (1990)<br>Static                                                | Digraph<br>Statistical                                               | 33                                | 0.25%                                 | 16.67%                                  |
| Bleha et al. (1990)<br>Static                                                 | Digraph<br>Statistical                                               | 10 (profiled)<br>26 (comparison)  | 2.8%                                  | 8.1%                                    |
| Legget et al. (1991)<br><sup>1</sup> Static, <sup>2</sup> Dynamic             | Digraph<br>Statistical                                               | 17                                | 5% <sup>1</sup><br>12.8% <sup>2</sup> | 5.5% <sup>1</sup><br>11.1% <sup>2</sup> |
| Brown & Rogers (1993)<br><sup>1</sup> Group 1, <sup>2</sup> Group 2<br>Static | Digraph<br>Combined Neural<br>Network & Statistical                  | 25 <sup>1</sup> / 21 <sup>2</sup> | 0%                                    | 4.2% <sup>1</sup><br>11.5% <sup>2</sup> |
| Napier et al. (1995)<br>Static                                                | Digraph<br>Statistical                                               | 67                                | 29.5% / 3.8%<br>(FAR + FRR)           |                                         |
| Mahar et al. (1995)<br>Static                                                 | Digraph<br>Statistical                                               | 67                                | 35% / 17.6%<br>(FAR + FRR)            |                                         |
| Furnell et al. (1996)<br><sup>1</sup> Static, <sup>2</sup> Dynamic            | Digraph<br>Neural Network <sup>1</sup> ,<br>Statistical <sup>2</sup> | 26                                | 8% <sup>1</sup><br>15% <sup>2</sup>   | 7% <sup>1</sup><br>0% <sup>2</sup>      |
| Guyen and Sogukpinar (2003)<br>Static                                         | Digraph<br>Statistical                                               | 12                                | 1%                                    | 10.7%                                   |

Table 5.1 - Previous keystroke analysis studies

The effect of an increased FRR is not so obvious when considering the classic C-I-A trio (Confidentiality, Integrity and Availability) as usually the only impact is on the latter, availability. Forgetting or mis-typing a password is a common occurrence and as such users may be somewhat forgiving of a system that asks them to re-type their password. However, if the supervision system is reliant on keystroke analysis it is not *what* the user types but *how* the user types that is important. A user is likely to become annoyed and confused at having to retype the same authentication details knowing that they are typing in the correct information. If the user is unaware that the system is also monitoring how they are typing this could result in poor acceptance of such techniques. As such, it is important to attain a balance between the two, or, to optimise the FAR to 0% whilst minimising the FRR to as near to 0% as possible.

There is also an issue of logged data size with the experiments summarised in Table 5.1. It is difficult to make direct comparisons based solely on the error rates without considering the size of the acquired data sets. While all the experiments listed provided details of the number of participants (ranging from 10 to 67), none provided details of the size of the sampled data. Without this information, the comparisons made between studies can only be based on the statistics available; namely the error rates, analysis method and number of participants. It is possible that the experiments achieving the best error rates could have been based on more samples than the others - in theory providing a broader range of samples on which to base a profile.

It should be noted that Table 5.1 does not fully reflect the entirety of published work in this domain, as a number of papers did not provide results in an appropriate format (i.e. the outcomes of the trials did not specify overall acceptance/rejection rates).

## 5.7 New approaches

The previous section summarised a range of published trials considering the application of keystroke analysis using digraph samples. It has already been indicated that there are other metrics that can be considered and the following sections will discuss the use of trigraph, keyword and application profiling. While these new approaches are not used in the initial trial described in the next chapter, the larger trial discussed in chapter 7 considers these methods in a practical implementation.

### 5.7.1 Trigraph/keyword profiling

Previous works have concentrated on the use of digraph profiles to authenticate users' typing patterns with few suggesting the possibility of using trigraphs - combinations of three characters (Song et al, 1997, Bergadano et al, 2002) or keywords. The use of trigraph profiling presents a wider range of available profile samples (i.e. the English language provides more three character combinations than two character) and also improves the likelihood of obtaining a wider range of timings (i.e. short digraph timings would be removed using the low pass filter whereas with trigraphs it is probable that a short timing on the first and second characters could be offset by a longer timing on the second and third character timings. It would still be necessary to have a high/low pass filter to cut off the extreme outliers, but this should still leave enough samples on which to base a profile. The same process applies to the application of keyword profiling; this could either be based upon a subset of commonly occurring words or based on specific rules (e.g. username or password)

Once enough data is gathered, it is likely that trigraphs would be evaluated in the same manner as digraphs, either adopting a statistical approach or using a neural network method (with a reduced range of trigraphs).

### 5.7.2 Application profiling

A further variation in the data analysis can be introduced through the consideration of application specific keystroke profiles. If we accept from previous work that individual users have a distinct typing pattern, it can be hypothesised that an individual's typing pattern may also vary depending upon the application in use. For example, a user participating in a chat session may type in a fairly relaxed conversational style, while the same user may type in a significantly different way when producing a document. As such, it may be possible to base an authentication judgement based on keyword timings.

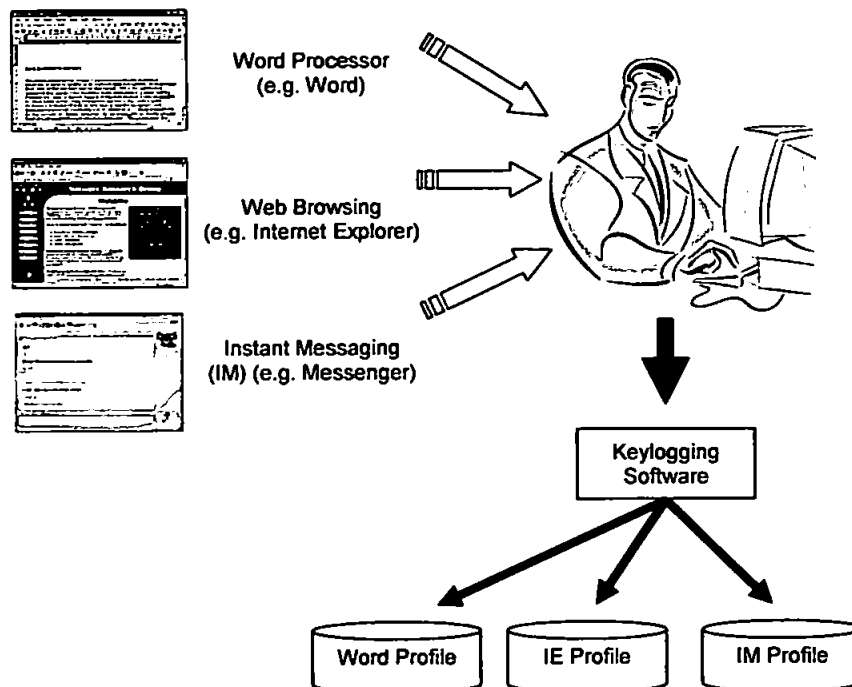


Figure 5.2 - Application profiling

### 5.7.3 Numeric profiling

It should also be noted that certain categories of user might use the numeric keypad for large quantities of data entry. Under these circumstances the volume and diversity of the keystroke digraphs will vary tremendously when compared to the more usual alphanumeric typing encountered with most user profiles. Previous research has been carried out in this area (Ord & Furnell, 2000), which has shown that analysis of numeric keystrokes can provide a viable authentication measure. This is an area receiving on-going attention through a separate research project in the Network Research Group (Clarke et al, 2003).

### 5.7.4 Composite keystroke dynamics

The results shown earlier in Table 5.1 demonstrated that the concept of keystroke analysis is feasible as an authentication mechanism. However, these trials were limited and provided variable results. While the approaches outlined in this chapter have focussed on the application of a single latency measure (i.e. using a digraph, trigraph or keyword method) it may be possible to obtain better results using a composite approach. By combining the confidence measures of multiple metrics (e.g. monitoring digraphs and trigraphs), coupled with monitoring specific keywords (e.g. the typing patterns for high-risk words – format, delete etc.), it may be possible to provide a higher level of confidence in the authentication of the user. The potential for this method will be considered further in a practical implementation in chapter 7.

## **5.8 Conclusions**

This chapter has considered the range of metrics available for monitoring keystroke analysis and the methods for processing such data. A number of possible additional measures have been identified that could be employed to improve the performance of digraph-only keystroke analysis.

The following chapter describes an initial trial investigating the application for keystroke analysis (digraph based) within a limited number of trial participants over a one-month period. While this trial only used digraph profiling, a later trial (discussed in chapter 7) profiled users based on digraph, trigram and word specific samples.

## **Chapter 6**

### ***System-Wide Keystroke Analysis***



## **6.1 Introduction**

In the previous chapter, the concept of keystroke analysis was introduced with a description of the various keystroke metrics that can be evaluated, together with an overview of the ways in which keystroke samples can be obtained. This chapter presents the results of a small-scale trial conducted to evaluate the viability of unconstrained, non-intrusive keystroke analysis (i.e. transparently monitoring a users' normal session). Before looking at the results, it is first necessary to describe the technical implementation of the software used to monitor the trial users, and to then consider the processing performed upon the acquired sample data.

This initial trial used an analytical approach for detecting deviation from a users' historical keystroke profile captured under a multi-tasking windowed environment. An alternative technique, a Data Mining (DM) approach, was also considered in order to determine the potential for improving user classification. These trials aimed to determine which approach provides the best basis for further research, and were not intended to produce a statistically valid conclusion (rather its aim was to provide a "proof of concept" that could then be used to demonstrate the viability of this approach).

## **6.2 Experiment Overview**

While keystroke analysis has been investigated (and hence implemented) in previous studies, a Graphical User Interface (GUI) environment (e.g. Microsoft Windows) introduces new challenges. In previous published studies, the user has been required to

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type and interact with a specific application (typing either pre-defined or free-form text). While this approach makes the development of the keystroke monitoring software simple, and maintains the consistency of the test environment, it is not representative of normal typing behaviour as the user becomes focussed upon the *task* of typing, rather than focussed upon a task that *involves* typing. If the aim is to produce static keystroke analysis for occasional authentication judgements (e.g. supplementing login authentication) then this approach will work well. However, to implement continuous supervision it is necessary to monitor the users' normal behaviour when interacting with their normal applications and operating system environment. Even providing a simulation of these environments may not be sufficient to obtain valid sample data on which to base a profile.

In order to address this problem, software was developed that would transparently monitor and log all typing activity. The system was designed to allow keystroke data to be collected under the Microsoft Windows NT environment (although the technique is equally applicable in all Microsoft Windows operating systems). In order to collect the required data, it was necessary to implement a mechanism for acquiring user typing patterns across all applications running within a users' active session. This is important as the experiment was designed to create a profile for each user based upon their typical typing patterns when using their computer (not constrained to a specific application or task). The implementation of the keylogger utilised several key features of the Windows operating system and the underlying chains of messages on which the operating system is built. These are briefly discussed in the following section.

### 6.2.1 Windows messages

The Windows operating system works on an event driven principle – when a key is pressed on the keyboard, or the mouse is moved, or any other *monitored* event occurs, the operating system generates a message that is sent to any application (or service) in the event chain.

If we imagine a hierarchy, representing the operating system and the applications running under it, messages are normally passed from the operating system, to each application registered to receive the appropriate messages. For example, almost all Windows applications process mousemove events – these are used to detect when the mouse has entered an application window. When an application is loaded, it notifies the operating system that it wishes to receive specific events when they occur, and from that point onwards the operating system provides notification of events to each application listed for each event. Windows applies a level of intelligence to message handling, such that when a notifiable event occurs (e.g. a keypress on the keyboard), the foreground application with the focus (i.e. the current application) will receive the message. This ensures that when typing into one application, others running in the background do not inadvertently receive the messages. However, if there are a series of applications that request the event notification, the events are passed through the event chain starting with the foreground application and working down to the most recent addition (Figure 6.1 shows this message handling in a simplified form).

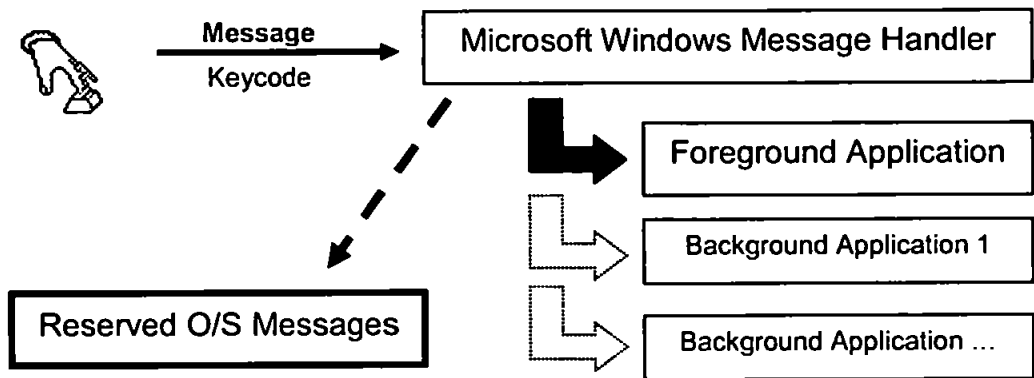


Figure 6.1 - Normal Windows messaging

When a key is pressed an event is raised in the operating system that is used to create a Windows message. Depending on the content of this message (the keycode in the event of a keypress), the message is routed to one or more applications or services. Generally (for keypresses) the message is directed at the current foreground application. However, if the message relates to a reserved operating system event (e.g. the CTRL-ALT-DEL sequence), this message is redirected to other system processes (e.g. the GINA DLL mentioned in the previous chapter). This is an important feature as, without it, an application would be able to obtain notification of the CTRL-ALT-DEL sequence and potentially override the underlying operating system's authentication routines. This could then be used (theoretically) to present a bogus login prompt with the aim of surreptitiously obtaining user login details.

In order to obtain keystroke messages under Windows (so that logging of keystrokes can occur across all applications) it is necessary to insert an application into the highest position of the event chain. This is important as once an application has received and processed a message (e.g. following a keypress event) it is removed from the hook chain and lower applications will not receive the message. To achieve this, a special form of

application must be written which implement a *system-wide* hook function. System-wide hooks allow a specified code block (the hook-function) to receive the required Windows messages irrespective of the target application (i.e. it is possible for a hook function to receive keystroke notifications for all currently running applications). This effectively allows application keystroke data to be *sniffed* and directed towards the data logger on the client workstation (Figure 6.2).

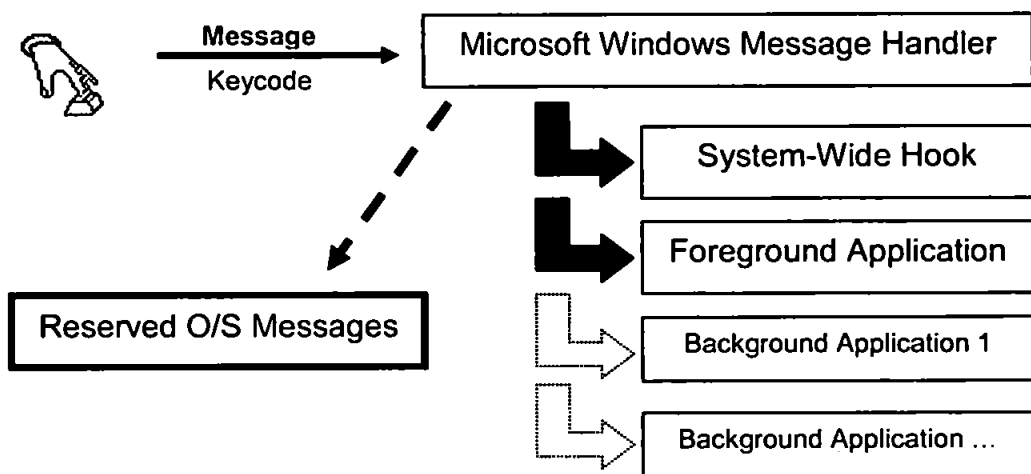


Figure 6.2 – Insertion of system-wide hook function

Once the hook function receives the message from the operating system it is important to ensure that the message is processed quickly and then sent on (dispatched) to the next application in the chain. If this is not done, the hook function (the keylogger in our case) will effectively absorb all keypresses and will not allow lower level applications to see any user activity – which is clearly undesirable.

6.2.2 System-wide hook implementation

The implementation of the keylogger required a system-wide hook to intercept all keystroke messages, and an application to filter and log keystrokes. The first attempt at implementing this utilised Visual Basic v6 Enterprise Edition to develop a simple application to log all keystrokes entered within the application window. Once the user had completed typing, the application would create a typing profile based upon typical typing patterns (illustrated in Figure 6.3). Figure 6.4 shows typing profiles from three different users with the lines indicating average typing speed per digraph. It should be noted that this application was a simple proof-of-concept program to determine the abilities of Windows to capture keystroke information and produce accurate digraph latencies transparently – no actual profiling was carried out based upon the results of this program and it is presented here simply to demonstrate the principle of capturing keystroke data.

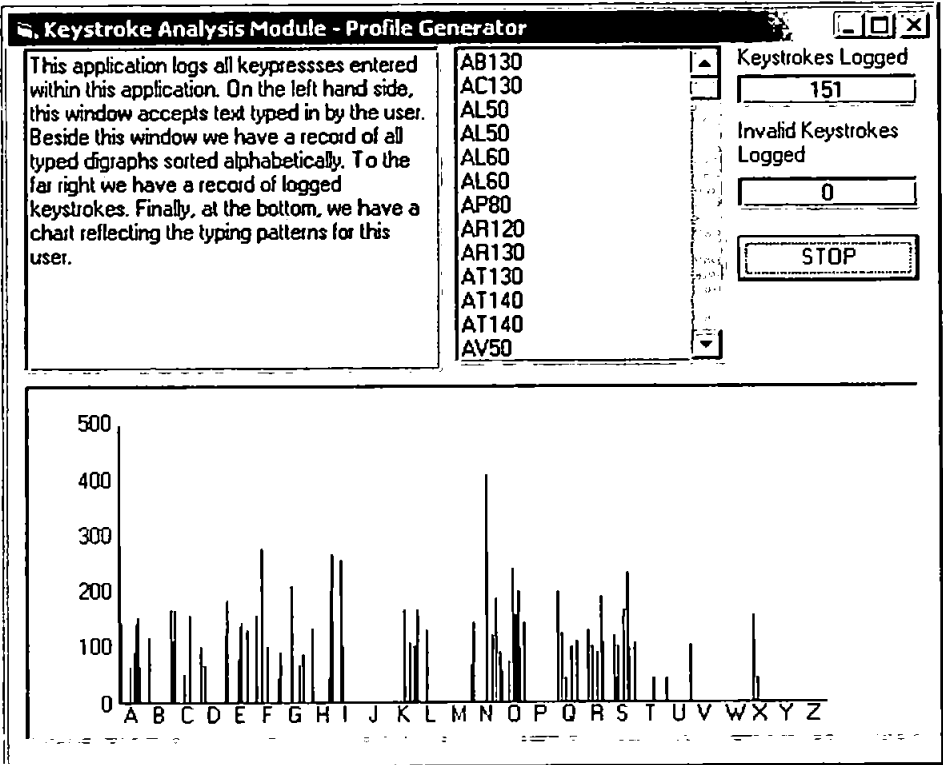


Figure 6.3 - Simple application for keystroke logging (vertical axis - time in ms)

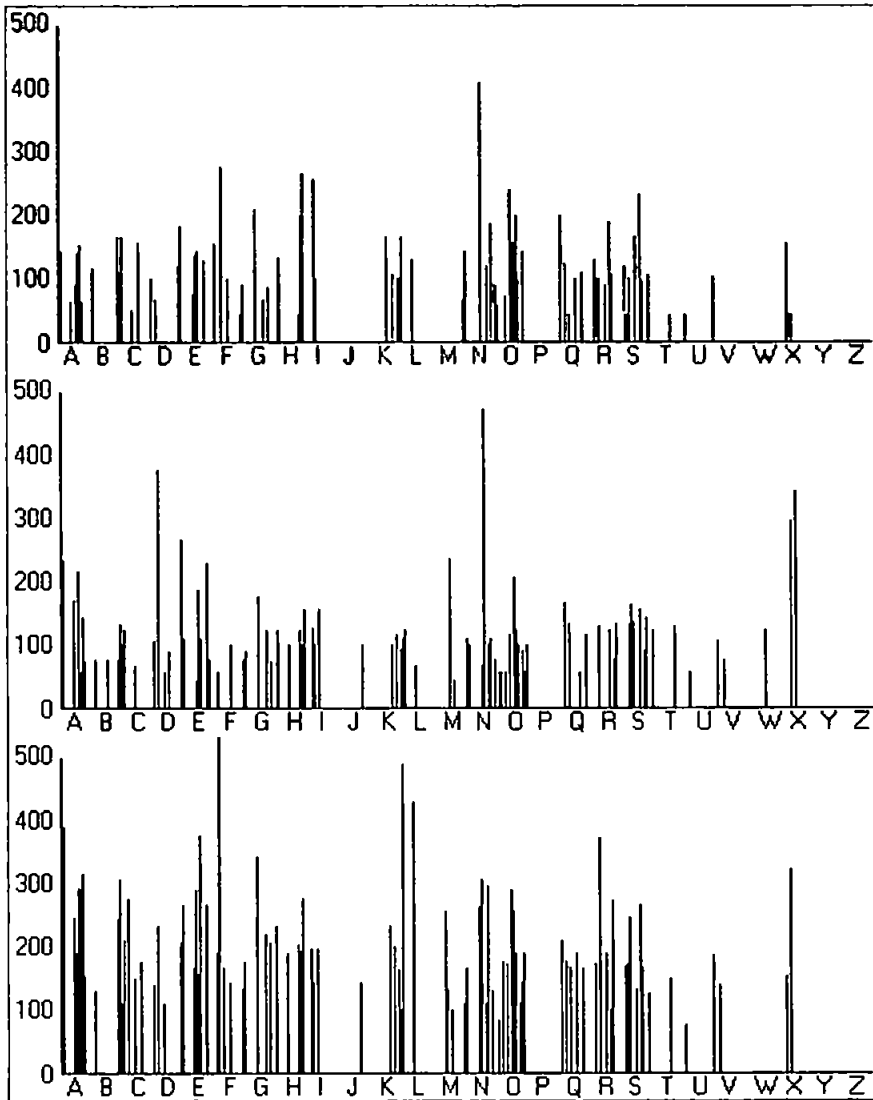


Figure 6.4 - Comparative profiles from three users (same typed text)

The digraph plots shown in Figure 6.4 show significant differences in typing patterns (particularly apparent in the third chart) – it should be noted that the actual digraph distribution varies slightly among the users as typing errors were also logged. While this application was able to successfully log all keystrokes typed within its text box, there were several limitations. The first (and obvious) limitation is that the keystrokes were only logged for the test application (i.e. all other applications were ignored). Secondly, and of more concern at this stage, was that the timing accuracy for digraph latencies were somewhat unreliable. A series of tests demonstrated that the timing resolution under

Visual Basic was in the order of 10 milli-seconds (the timings shown in Figure 6.3 show a resolution of 10ms) – far too large for keystroke latencies which are expected to be in the range 40-750ms (i.e. a 10ms resolution may not provide sufficient distinction between user samples). In order to address this, further investigations were conducted to locate a more accurate timer. The obvious alternative was to use the Windows API `GetTickCount()` function – while this provides a timer with a resolution of 1ms, it is somewhat unreliable as the counter used by this function uses a fixed range data type and can overflow (wraps around back to zero) there are also problems due to locking of threads that prevents the `GetTickCount()` function registering CPU cycles. Fortunately the Windows Application Programming Interface (API) provides another alternative, a simple solution in the form of the `QueryPerformanceCounter` (located in the kernel DLL).

The `QueryPerformanceCounter` functions provide access to a “high-resolution performance counter” (Microsoft, 2004). Using the two counter functions it is possible to obtain a timer with a resolution of approximately 1 $\mu$ s (Table 6.1).

| Function                               | Purpose                                                                                                                                                                                                                              |
|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <code>QueryPerformanceCounter</code>   | Returns a large integer equivalent to the tick-count (i.e. number of clock ticks since boot time).                                                                                                                                   |
| <code>QueryPerformanceFrequency</code> | Returns a large integer containing the performance-counter frequency, in counts per second. This can be used to determine the number of clock ticks occurring per second and hence convert the counter value into a time in seconds. |

Table 6.1 – Timer functions under Windows API

The functions listed in Table 6.1 are available in all versions of Windows from Windows 95 onwards – however, not all computer systems provide access to this counter (the high-



performance counter is a feature of the system's CPU and almost all processors since the 386 support this, however, it is still hardware dependent). It is therefore important to check the return values of these functions to ensure that the counters are actually available on the system under test.

To use these timer functions for digraph latency timings, the counter needs to be stored when the first keystroke is released (time1) and at second keystroke is pressed (time2). To determine the latency in seconds it is necessary to use both functions together. Subtracting the times provides the number of counter intervals that have occurred between the keystrokes, which can then be divided by the counter frequency to give a time in seconds (the inter-keystroke latency).

$$\text{latency} = (\text{time2} - \text{time1}) / \text{frequency}$$

Having obtained the necessary timing resolution, the problem of system-wide keystroke capture was addressed. The common approach to this problem is to implement a system-wide hook to capture all events of a specific type (keypresses in this case). This however was not possible in Visual Basic. To intercept keyboard messages it is necessary to call the SetWindowsHookEx function in the Windows API (code below). As part of this function call, a pointer is passed providing the memory address of a function to receive the intercepted messages. While Visual Basic (VB) is able to provide a function to receive the messages, it cannot be accessed by other applications (i.e. the messages must have originated within the VB application). The normal method for implementing system-wide hooks is to implement the code in a standard Windows Dynamic Link Library (DLL) file. Unfortunately VB is unable to produce standard DLL's (VB can however create OLE-DLL

files – but these are very different in structure). To resolve this problem, a DLL had to be written in Visual C++ v6 (VC) in order to create the necessary code.

```
HHOOK SetWindowsHookEx(idHook, lpfn, hMod, dwThreadId)
```

**Parameters:**

idHook – Specifies the type of hook procedure to be installed.

lpfn – Pointer to the hook procedure.

hMod – Handle to the DLL containing the hook procedure.

dwThreadId – identifier of the thread with which the hook procedure is to be associated

**Code Sample 1 - SetWindowsHookEx() function prototype**

The important parameter is the final one. The dwThreadId parameter specifies which thread (effectively which application) the hook will be installed for. While VB was able to install a hook, its use was constrained to the current thread (i.e. the application calling the function). To enable a system-wide hook across all threads (and hence all applications) it is necessary to pass the value zero – this will then ensure that the hook procedure is associated with all existing threads running in the same desktop as the calling thread.

Finally, the code to process the messages was developed. This function had to evaluate each Windows message in turn to check the nature of the message and to then pass this information back to a program that could process and log each keypress/release event. It was decided that this would be a two-stage process. Windows messages would be received by the KeyboardProc function (the keyboard system-wide hook function) and would then be filtered. Keypress events (both key-up and key-down messages) would then be sent to a VB application for further processing and logging. This sequence is represented in Figure 6.5.

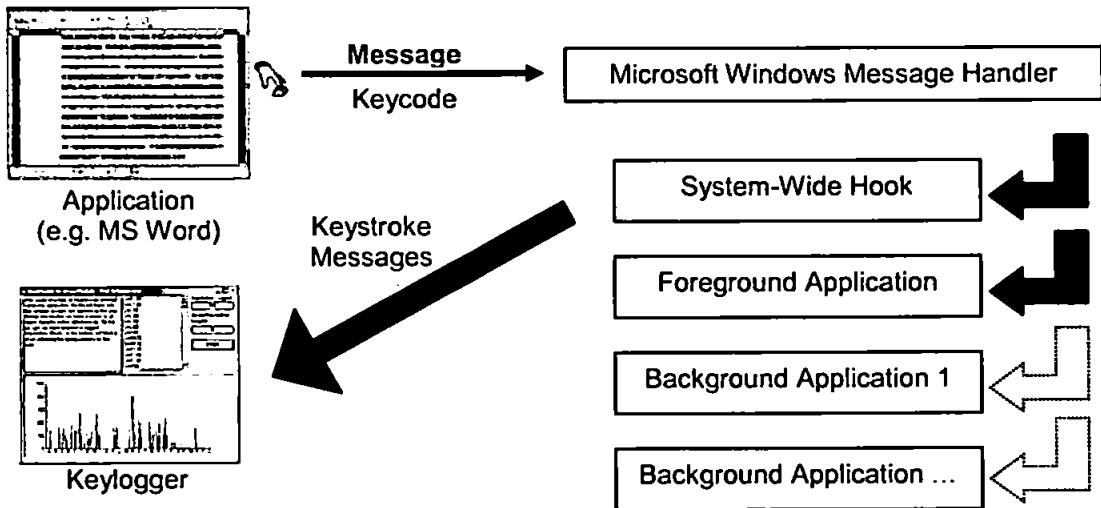


Figure 6.5 - Keylogger inserted with system-wide scope

To send the keystroke data to the keylogger, messages were directly sent to the VB application replicating the keypresses received by the hook function (and destined for the original target application). This effectively meant that the keylogger saw all system-wide keypress events as if they had occurred locally within the VB application. This was achieved by using the `PostMessage` API function to notify the target application (the keylogger) of a specific event. This is the same process used by Computer Based Training (CBT) packages to take remote control of an application and demonstrate normal user interaction e.g. typing and mouse movements (this is usually referred to as *injecting* messages).

The KeyboardProc function code (to receive and process keypress messages) is listed in Code Sample 2.

```

LRESULT VK_KEYBOARDHOOK_API __stdcall KeyboardProc(int nCode, WPARAM wParam, LPARAM lParam)
{
    //Only examine HC_ACTION messages - other messages contain no data.
    if (nCode==HC_ACTION)
    {
        //Handle key-up action
        if (HIWORD(lParam) & KF_UP)
        {
            PostMessage(loggerWindow, WM_KEYUP, wParam, lParam);
        }

        //Handle key-down action.
        else if (!(HIWORD(lParam) & KF_UP)) & (!(HIWORD(lParam) & KF_REPEAT)))
        {
            PostMessage(loggerWindow, WM_KEYDOWN, wParam, lParam);
        }
    }

    //
    // Once we have looked at the message and passed it to the keylogger
    // the message must be passed to the original application
    // We will pass all messages on to CallNextHookEx.
    //
    return(CallNextHookEx(keyboardHook, nCode, wParam, lParam));
}

```

Code Sample 2 - KeyboardProc() implementation

As messages are received they are split into key-up and key-down events. Key-down events are further checked to eliminate repeat keys (i.e. when a key is held down causing multiple, repeated characters). Messages are then posted to the VB keylogger (which then sees the key events as local keypresses) and finally the original message is sent on to the original destination (e.g. to Microsoft Word). The wParam value holds the virtual key-code for the keypress event, while the lParam value holds a 32 bit value where the bit sequences indicates additional parameters, such as the nature of the keypress event (key up, down or repeat), the number of repeat occurrences of the key, scan-codes and the status of the extended keys (e.g. the ALT key). Keyboards generate scan-codes for each keypress/release – with each key generating a unique *make* and *break* scancode. Scan-codes provide low-level keyboard information – e.g. the ability to distinguish between the numerals at the top of the letter keys and those found in a dedicated numeric keypad.

An additional feature was introduced to the hook function to monitor the handle of the application in which the keypress occurred (a handle is a numeric value that uniquely identifies the application window within Windows). This would allow the keylogger to also record the title of the foreground application window (i.e. the program in which the user was actively typing). The code for this is presented below and simply monitored the foreground window handle for any change. When a change in application focus occurred, the keylogger was notified of the change of focus by a Windows message – as keypress message were already in use to notify the keylogger of keyboard activity, the keylogger was notified of a change of application focus by sending a left button mouse-click message. This would then allow the keylogger to request the title of the application window (via the API) and subsequently log this information, together with the keystroke data and the username of the currently logged in user.

```
hwndCurrent=GetForegroundWindow();
if (IsWindow(hwndCurrent))
{
    if (hwndCurrent!=hwndLast)
    {
        PostMessage(loggerWindow, WM_LBUTTONDOWN, MK_LBUTTON, 0);
    }
    hwndLast=hwndCurrent;
}
```

**Code Sample 3 - Notification of application focus change**

### 6.2.3 Keylogger implementation

The VB keylogger had a relatively simple implementation. Once started, the application loaded the hook function into memory by initiating the DLL file. The hook function was then inserted into the message event chain with system-wide scope. As part of this, the hook function was also passed a handle to a picture box located on the keylogger interface.

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This control was chosen as it can receive keystroke and mouse click messages while presenting no visual interface – i.e. if a user opened the application they would not be able to interfere with the key logging process. This handle was used by the hook function to post messages directly to the VB keylogger application (Figure 6.6).

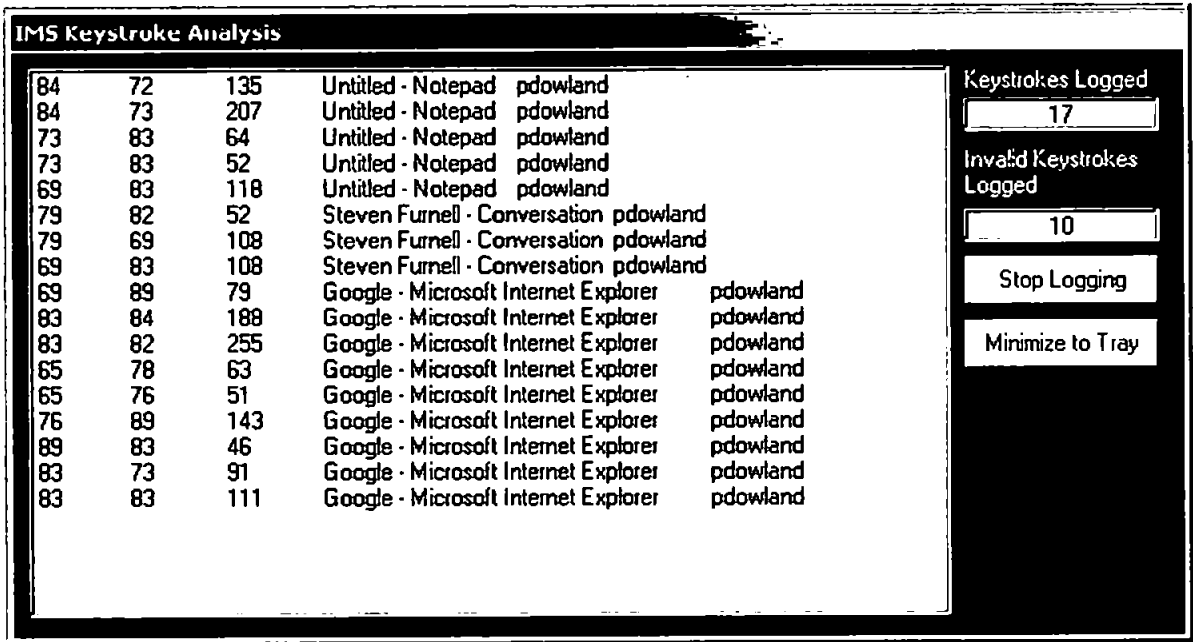


Figure 6.6 - Key logging across multiple applications

When running, the keylogger was discreetly added to the system tray to avoid any inconvenience to the user (shown as the furthest right icon in Figure 6.7).

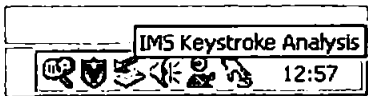


Figure 6.7 - System tray icon for keystroke analysis

For each digraph pair logged, the application stores five items of information – these being written to a text file after every 500 digraphs (Table 6.2).

| Item            | Data types                                                          |
|-----------------|---------------------------------------------------------------------|
| Left character  | ASCII code representing character                                   |
| Right character | ASCII code representing character                                   |
| Latency         | Integer representing inter-keystroke latency in milliseconds        |
| Application     | String containing the window title from the foreground application. |
| Username        | String containing currently logged-in user                          |

**Table 6.2 - Keylogger attributes logged per digraph**

### **6.2.4 Filtering**

To eliminate extreme short/long digraph latencies that may adversely affect the distribution of digraph times, any digraph pair whose latency fell outside a nominal range was excluded from the log files. For the purpose of this experiment the range was restricted to times above 40ms and below 750ms. These thresholds were based on previous work conducted by Furnell (1995), and were designed to eliminate samples where two keys may have been accidentally struck together (thus, producing an infeasibly small latency) or, where the user may have made a pause in their typing and thus introduced an unnaturally large inter-keystroke latency.

## **6.3 Final implementation**

The final implementation of the keylogger application is shown in Figure 6.8. This shows the messages passed from the hook (implemented in the DLL in C) and the keylogger (implemented in Visual Basic and deployed as a system tray application). The keylogger functioned completely transparently to the user, requiring no user action to start or stop the logging process. The application was automatically started when the operating system (O/S) booted (run from the Startup program group on the start menu) and shut down

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automatically when the O/S closed. Gathered data was automatically saved after every 500 digraphs pairs and when the application was closed. To reassure users, an option was included to suspend logging of keystrokes. This was included due to concerns expressed by some users about monitoring of specific inputs – e.g. the typing of on-line banking login details.

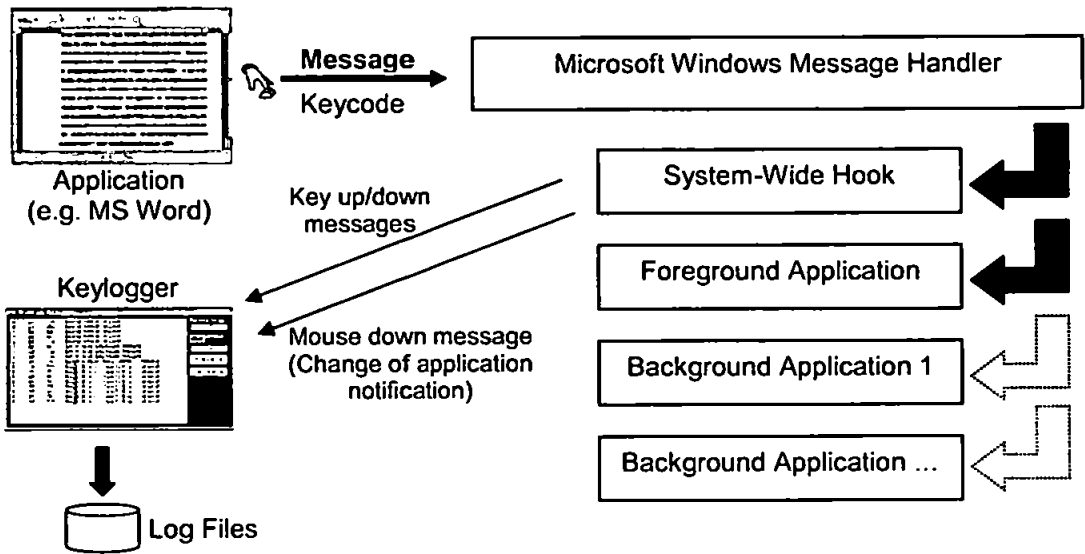


Figure 6.8 - Final implementation of keylogger

## 6.4 Trial participants

For this experiment a total of ten users were profiled over a period of three months. The trial participants were drawn from students and staff from the Network Research Group. As the intention was to evaluate the analysis mechanisms without implementing a large-scale trial, tests were carried out using a small set of test subjects. The main limiting factor was the need to collect data over a prolonged period (weeks rather than hours). Despite the small scale of the trial, it still proved difficult to collect sufficient data in order to provide a



valid comparison between users. Several users disabled the keylogger when entering sensitive information and consequently forgot to re-enable it. This resulted in large variations in profile size (discussed in the following section).

Due to this limited set of data, some of the discussion and analysis in the following sections focuses on the six main users who provided the largest profiled data sets in order to best illustrate the trends observed.

## **6.5 Analysis**

Following the initial filtering described in the previous section, the experimental data for each user was processed off-line to calculate the mean and standard deviation values for each unique digraph pair. In the event that any digraph pair had a standard deviation greater than its mean value, the digraph samples were sorted and the top/bottom 10% were then removed, followed by subsequent re-calculation of the mean and standard deviation values – this was only attempted where at least ten samples were available for the digraph pair. The reason for this additional step was to remove digraph samples where the latencies would have an adverse affect on the standard deviation (i.e. the distribution of samples was tightened).

Once a profile of digraph pairs was produced (with corresponding mean/standard deviation digraph latency values), the user's profile was further constrained by filtering out digraph pairs where the sample count fell below a nominal threshold value. This initial experiment fixed this value at fifty samples; however, the software used for analysis allowed a variable threshold (Figure 6.9).

**Key Logger Analyser**

---

**Profile Information**

Select profile:

Minimum Samples per Digraph:

☒ SDev>Mean Compensation

Total Digraph Samples:  Unique Digraph Pairs:

---

**Initial Results**

| Digraph | Time | Mean     | SDev     |
|---------|------|----------|----------|
| AC      | 165  | 142.8... | 39.49... |
| AD      | 88   | 150.5... | 79.45... |
| AE      | 105  | 212.3... | 71.51... |
| AI      | 59   | 101.6... | 88.87... |
| AL      | 175  | 137.2... | 112.5... |
| AN      | 147  | 105.5... | 81.99... |
| AR      | 235  | 158.8... | 79.34... |

Reduced Digraph Pairs:

Average Digraph Latency:

Finished

---

**Test Profile**

Select profile:

Number of Standard Deviations:

---

**Results**

|                                 |                                      |                                          |                                      |
|---------------------------------|--------------------------------------|------------------------------------------|--------------------------------------|
| Total Digraph Samples:          | <input type="text" value="15613"/>   | Analysed Digraphs:                       | <input type="text" value="10237"/>   |
| Highest Cumulative Alert Level: | <input type="text" value="19"/>      | Highest Consecutively Rejected Digraphs: | <input type="text" value="7"/>       |
| Accepted Profiled Digraphs:     | <input type="text" value="7420"/>    | Rejected Profiled Digraphs:              | <input type="text" value="2817"/>    |
| %ge Alert Level:                | <input type="text" value="0.18560"/> | %ge Accepted Digraphs:                   | <input type="text" value="72.4821"/> |

Figure 6.9 - Profile generation and testing

The profile generator and analyser is split into four separate sections with a number of options/results displayed. This is discussed in the following sections.

### 6.5.1 Profile settings

Figure 6.10 shows the profile selection frame within the application. This allows the selection of the original user keylogger data files (stored as a plain text file) and options to change the minimum number of samples per digraph, as well as the option to re-calculate digraph sets where the standard deviation is greater than the mean. The first setting allows a variation in the minimum number of samples required to produce a viable digraph profile. This ensures that only digraphs with a large number of samples are used in the final profile. The example in Figure 6.10 shows a profile loaded containing 15,613 individual digraph samples (a very small data set) which comprises 469 unique digraph pairs – this gives an average of only 33 samples per digraph. By applying a threshold value (set to 50 in the figure) the least frequently occurring digraphs are removed from the final profile.

Profile Information

Select profile: C:\Documents and Settings\Administrator\My Documents\Work Select

Minimum Samples per Digraph: 50

☒ SDev>Mean Compensation Analyse

Total Digraph Samples: 15613 Unique Digraph Pairs: 469

Figure 6.10 - Profile selection

The setting to select filtering of digraphs where the standard deviation is greater than the mean is used to filter digraphs with high variance. Where this condition is found true, the top/bottom 10% of samples are removed and the standard deviation and mean are recalculated with this process repeated until the variance is reduced. This will result in a digraph pair being removed from the profile altogether if the number of eligible samples is reduced below the threshold set in the first option. To give an indication of this, the test

run shown in Figure 6.9 resulted in the number of profiled digraphs being reduced from 469 to just 92.

6.5.2 Generated profile

Figure 6.11 shows the profile generated from the selected keylogger data file following the processing selected and described in the previous section. The reduced set of digraphs (92 in this example) are shown together with their associated mean and standard deviation values. Note that the digraphs are sorted alphabetically rather than by frequency of occurrence – this was by design to allow rapid searching of the profile for specific digraph pairs when comparing raw keylogger data files. The variance shown between digraphs is quite significant – the digraph pair A-C has a profile of 142.8ms ± 39.49 while the digraph pair A-L has a profile of 137.2ms ± 112.5. This variance can be adjusted in the later settings described in the next section.

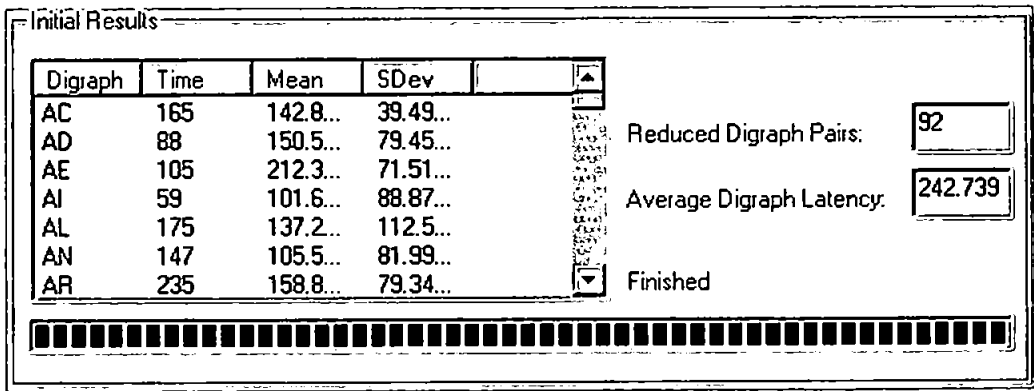


Figure 6.11 - Generated profile

6.5.3 Test profile selection and settings

Figure 6.12 shows the test profile settings frame. In this section the comparison keylogger data file is selected (the users' data that will be compared against the generated profile) and the level of deviation from the profile is determined. When the comparison is started, each digraph is compared against the reference profile and a simple analytical comparison is performed. If the test digraph is within the permitted range of the reference profile the digraph is accepted. The permitted deviation is determined by the slider control that selects the number of standard deviations from the mean.

$$\text{digraph mean} \pm (\text{digraph standard deviation} * \text{permitted deviation})$$

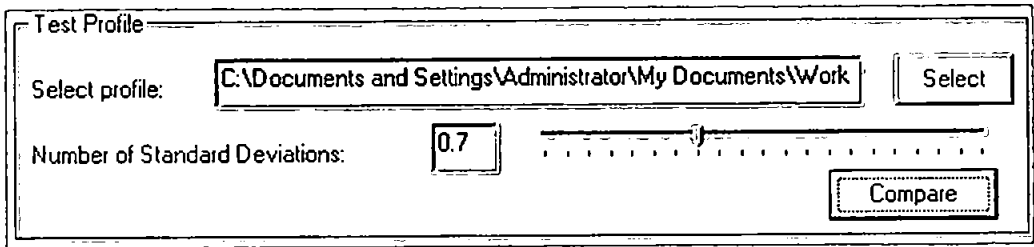


Figure 6.12 - Test profile selection and settings

The comparison described above is repeated for each captured digraph in the comparison keylogger data file and a number of statistics calculated (described in the next section).

6.5.4 Test profile results

Figure 6.13 shows the results frame. This presents the results from the analysis conducted on the keylogger data file when compared against the reference profile. In total eight values are presented, as described in Table 6.3.

| Results                         |         |                                          |         |
|---------------------------------|---------|------------------------------------------|---------|
| Total Digraph Samples:          | 15613   | Analysed Digraphs:                       | 10237   |
| Highest Cumulative Alert Level: | 19      | Highest Consecutively Rejected Digraphs: | 7       |
| Accepted Profiled Digraphs:     | 7420    | Rejected Profiled Digraphs:              | 2817    |
| %ge Alert Level:                | 0.18560 | %ge Accepted Digraphs:                   | 72.4821 |

Figure 6.13 - Test profile results

| Item                                    | Description                                                                                                                                                                                                                                                         |
|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Total Digraph Samples                   | Total number of digraphs in the keylogger data file.                                                                                                                                                                                                                |
| Analysed Digraphs                       | Total number of digraphs that match digraphs in the comparison profile.                                                                                                                                                                                             |
| Highest Cumulative Alert Level          | A running alert level is maintained which is incremented/decremented with each digraph decision. A live system would need a threshold value (probably individually set for each user) beyond which the user would be more explicitly challenged for authentication. |
| Highest Consecutively Rejected Digraphs | A count of the highest number of consecutively rejected digraphs. This may provide evidence of a poor match between reference profile and comparison keylogger file.                                                                                                |
| Accepted Profiled Digraphs              | Total number of accepted digraphs (i.e. those that match the reference profile within the permitted deviation).                                                                                                                                                     |
| Rejected Profiled Digraphs              | Total number of rejected digraphs (i.e. those that do not match the reference profile $\pm$ permitted deviation).                                                                                                                                                   |
| %ge Alert Level                         | Alert level represented as the highest alert level divided by the number of analysed digraphs.                                                                                                                                                                      |
| %ge Accepted Digraphs                   | Percentage of digraphs accepted – provides an indication of the goodness of the match between reference profile and comparison keylogger data file.                                                                                                                 |

Table 6.3 - Description of profile comparison results

## 6.6 Results

Although ten users participated in the trial run, only eight produced enough data to warrant further investigation. A summary of the user data generated in this trial is shown in Table

6.4. This shows considerable variation in the size of keylogger data files across the eight users with sample sizes in the range 7,000 to 350,000 digraphs. As such, users f and g were removed from most of the data processing as the quantity of the logged keystrokes was too small to provide a reliable profile (i.e. there were too few digraph pairs in the profile, with too few samples per profiled digraph).

| User   | Total Digraph Samples | Unique Digraph Pairs | Filtered Digraph Pairs | Average Typing Speed |
|--------|-----------------------|----------------------|------------------------|----------------------|
| User A | 178,710               | 466                  | 317                    | 151ms                |
| User B | 59,787                | 405                  | 232                    | 145ms                |
| User C | 80,167                | 412                  | 257                    | 206ms                |
| User D | 58,987                | 461                  | 224                    | 162ms                |
| User E | 15,613                | 469                  | 92                     | 243ms                |
| User F | 8,696                 | 391                  | 55                     | 285ms                |
| User G | 7,435                 | 405                  | 42                     | 272ms                |
| User H | 350,567               | 610                  | 369                    | 297ms                |

Table 6.4 - Summary of user profile statistics

Once each user profile was generated, the reference profile was evaluated by comparison against the users' raw keylogger data. This allowed the test profile to be evaluated using the users' own data (to test the False Rejection Rate – FRR) and against other users' keystroke data (to test the False Acceptance Rate – FAR).

As there is likely to be significant variation in a users' own session data, a compensatory factor was applied to the standard deviation that could be varied in a "live" environment according to the security needs of the organisation. This factor allowed the number of standard deviations from the mean to be adjusted. For the purposes of this experiment, four weightings were considered, namely 0.5, 1, 1.5 and 2. These weightings were selected based on experimental work by Mahar *et al.* (1995) This produced an acceptable digraph range:

$$\text{digraph range} = \text{mean} \pm (\text{standard deviation} * \text{weighting factor})$$

When viewing the preliminary results (Figure 6.14), if we consider the six users A, B, C, D, E and H and follow the vertical columns of data, we can see a peak for each user's data when compared with their own profile. This is most noticeable for user D where a peak is observed (nearly 50% of all digraphs accepted) compared with 32% when user B's raw keylogger data was tested against the same profile.

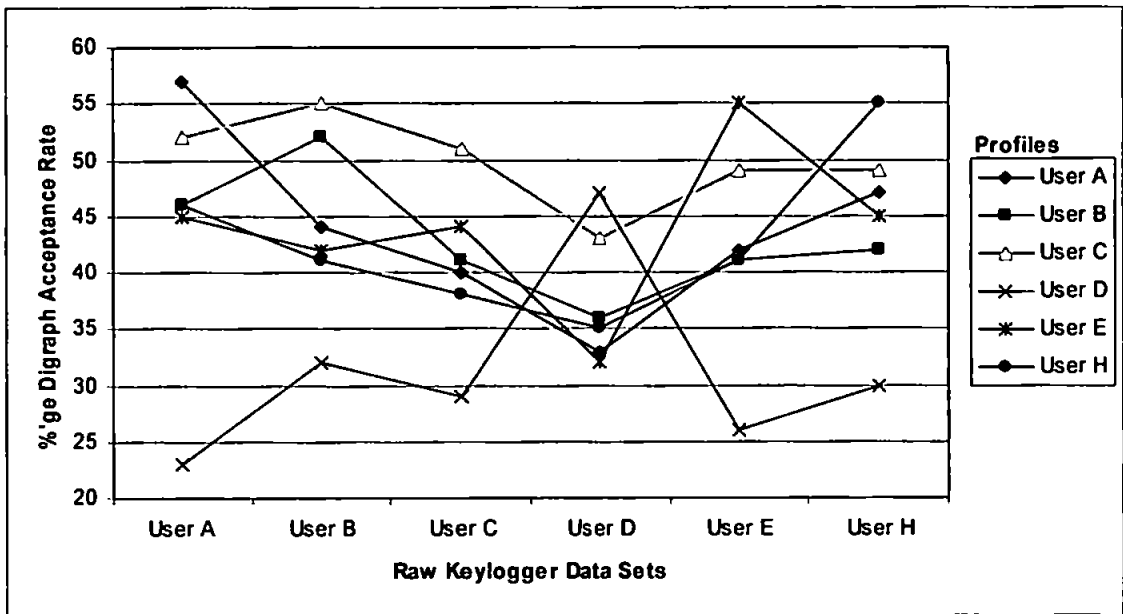


Figure 6.14 - User profile comparisons

Although there was a correlation between user D's profile and data, if we consider user A, there was a high FAR for data from users B and H (impostors) when compared with user A's profile. We can also see that in user C's profile the impostors A and B actually achieved higher acceptance rates (52% and 55% respectively) against the valid user (C) with only 51%. It is clear from these results that an additional measure of acceptance/rejection is required. To further test the FAR/FRR of the test system, the analysis software monitored the number of consecutively rejected digraph pairs – representing the highest alert level of the system (Figure 6.15 & Figure 6.16). Further



charts, presenting the comparison of all user data against all profiles can be found in Appendix B.

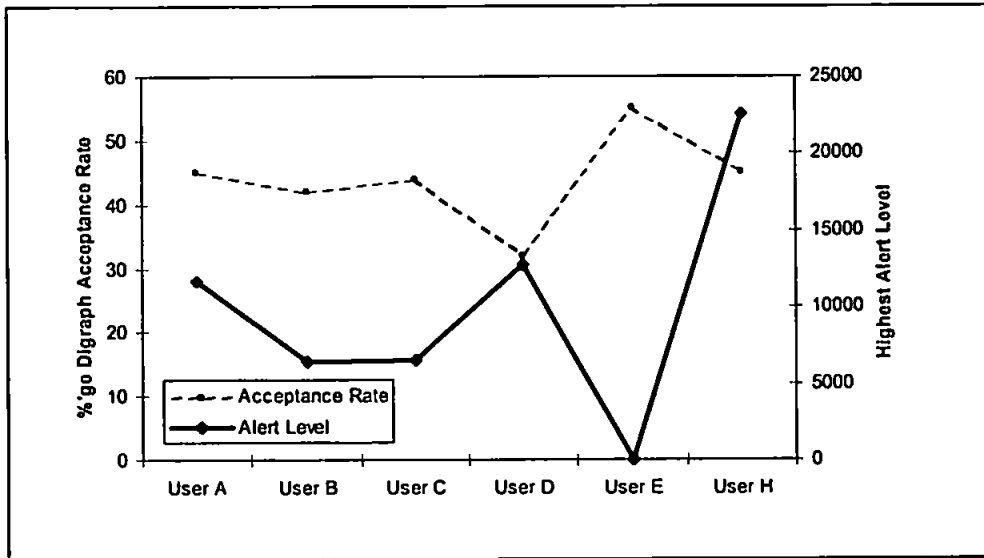


Figure 6.15 – User E profile comparison

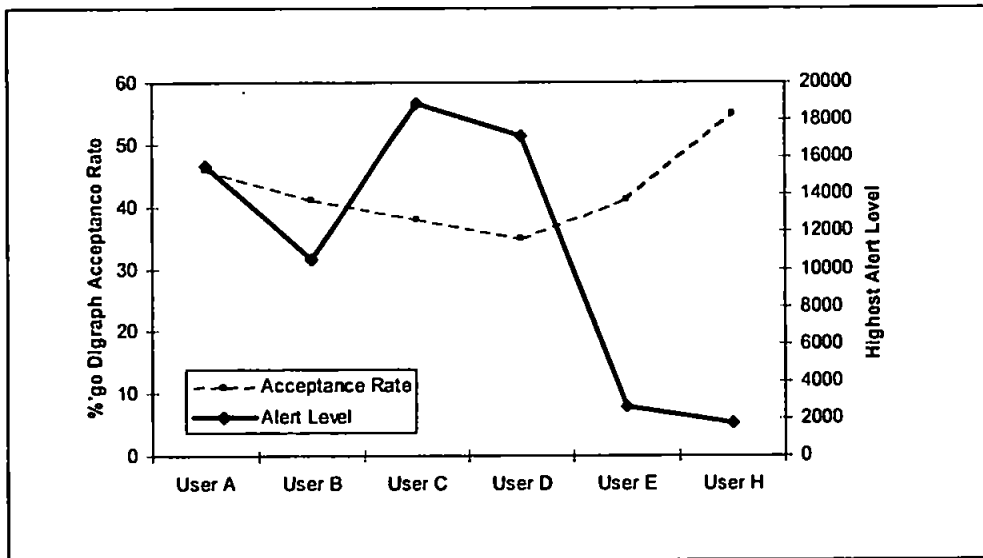


Figure 6.16 - User H profile comparison

When considering Figure 6.15 we can identify two distinct trends. Firstly, the top line plots the digraph acceptance rate for all user data sets against user E's profile. Here we can see a peak correlating to user E's own data and corresponding reductions in the acceptance

rates for the other users' data. Secondly, the lower line indicates the highest alert level detected by the analysis software. This is simply a record of the highest count of consecutively rejected digraph times (excluding non-profiled digraph pairs). Again, we can see a correlation between user E's own data when compared with their profile, and corresponding increases in the alert level as impostor data sets are compared with the target profile. Figure 6.16 further demonstrates this using user H's profile. User H also shows a significant correlation between their own profile and raw keylogger data. It is important to note that while the charts shown here (and in Appendix B) show simple comparisons between profiles, a live system would utilise thresholds for each user that would be used to determine the acceptance/rejection level for each user. For example, in Figure 6.15, user E's rejection rate is significantly smaller than even the closest impostor. It would be possible (for this user) to assign a relatively low threshold for consecutively rejected digraphs as user E had a highest count of 42 consecutively rejected digraphs whilst users B and C had counts in excess of 6000 when compared to user E's profile (i.e. as impostors).

## **6.7 Data mining analysis**

The previous sections have considered a simple analytical approach to the problem of keystroke analysis. While this approach has shown some success both in this trial and in previous work, there are other alternatives that can be considered. One technique that was evaluated was the use of Data Mining (DM) algorithms, a previously untried approach in this field. This work was conducted in association with Harjit Singh and is covered in detail in Singh et al (2001). This part of the study will not be covered in detail here, except

to compare the FAR/FRR percentage accuracy with the approach used in the previous sections.

### 6.7.1 Methodology

For the DM analysis, the data sets were split into a ratio of 9:1 creating two parts; a training set and a testing set. The Intelligent Data Analysis (IDA) Data Mining Tool (Singh et al, 1999) was used to analyse the sample data sets. The IDA tool incorporates algorithms from the fields of Statistics, Machine Learning and Neural Networks, with six algorithms being selected (k-NN, COG, C4.5, CN2, OC1 and RBF). The algorithm or classifier was subjected initially with the training set, and then the classification accuracy was tested using the unseen data set or testing set. The results give an indication of the error rate (or FAR) and the overall classification accuracy of the trained algorithms.

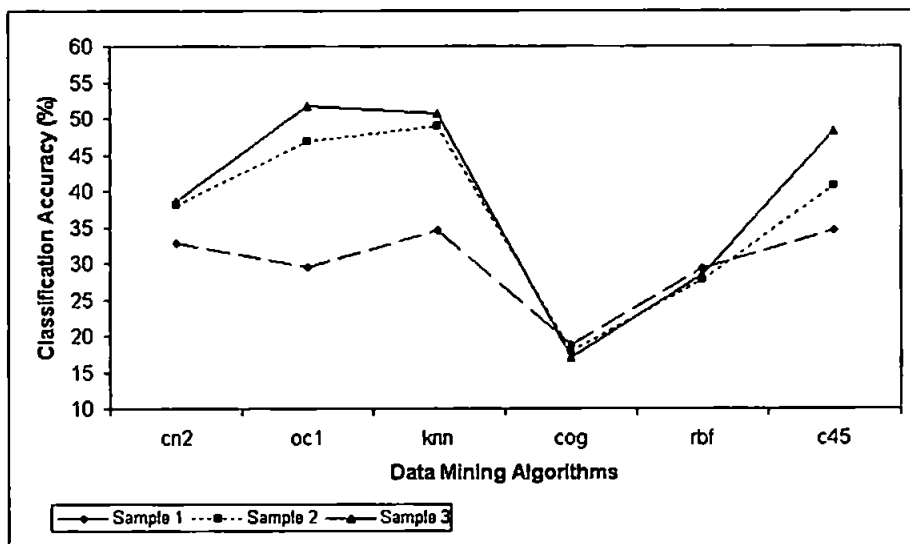


Figure 6.17 - Varying sample sizes with fixed number of classes and attributes

The percentage classification accuracy obtained is encouraging as depicted in (Figure 6.17), which shows that when the sample size is increased, the classification accuracy obtained

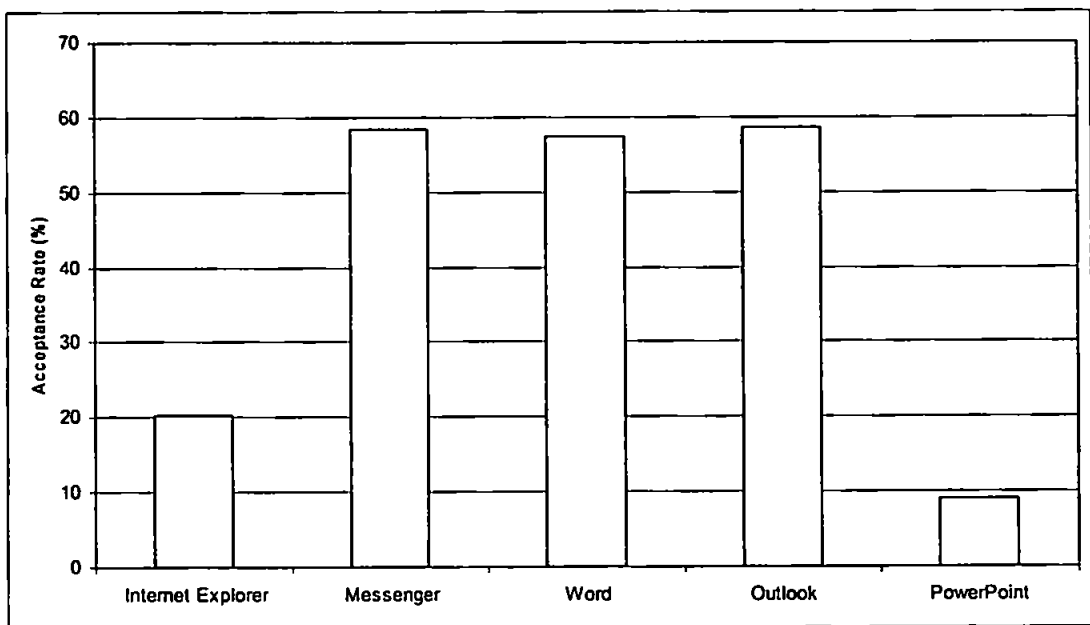
increases proportionally, except for COG (a statistically based algorithm) and RBF (a Neural Network based algorithm). This is important when considering the size of data being analysed.

The initial results suggest that Machine Learning (OC1 and C4.5) and Statistical (k-NN) based algorithms are suitable for these types of data sets. While these results show a classification accuracy approaching 50%, this is still far short of an acceptable level of false rejection. It is likely that with more data, and a reduced set of core (commonly occurring) digraphs, higher classification accuracies would be attainable. However, these techniques are still of marginal benefit due to the time taken to process the data sets. As such, this study proceeded with the analytical approach and the application of data mining to keystroke analysis will be revisited in chapter 9 as part of the future work proposals.

## **6.8 Application-specific keystroke analysis**

Following the digraph-based keystroke analysis discussed earlier in this chapter, the final investigation considered the use of application-specific keystroke analysis. In this case, the analysis was conducted with a view to determining the viability of application-specific keystroke profiling (referring back to Table 6.2, the application from which the keystrokes were typed was logged in addition to other characteristics). To this end, it was necessary to identify a series of applications for profiling, with the selection criteria being those for which sufficient keystroke data had been logged during the sampling period. A review of the keystroke data revealed that the applications satisfying this requirement were Microsoft MSN Messenger, Internet Explorer, Word, Outlook and PowerPoint. While it was

considered that a numerically intensive application such as Excel would have provided an interesting candidate, insufficient keystrokes were captured to enable the creation of a profile. Additionally, of the eight users sampled during the trial (who produced sufficient data for digraph analysis), only five produced sufficient samples to analyse from all of the aforementioned applications. Although the resulting sample group was very small, it was sufficient to yield interesting results in relation to an initial assessment of application-specific profiling.



**Figure 6.18 - Acceptance rate for application specific keystroke data compared against a system-wide context user profile**

In Figure 6.18, a single user's application-specific keystroke data is compared against the reference profile from the same user. The reference profile was based on all keystroke data acquired from all applications. Although the figure does not show distinct differences in all cases, there is a clear distinction between PowerPoint & Internet Explorer and Messenger, Word & Outlook. This can be explained when the nature of these applications is considered. Messenger, Word and Outlook are all significantly textual in their usage, and users will typically type within them for considerable periods of time. In contrast, while

Internet Explorer and PowerPoint sessions may both involve significant elements of keyboard activity, the typing is more likely to occur in sporadic bursts. As such, any dynamic that emerges is likely to be markedly different to that which would emerge in applications where more sustained typing is the norm. Considering the information portrayed above, the creation of application specific profiles would be likely to increase the acceptance rates observed. This could be significantly more effective given more keystroke data - it may be possible (with sufficient data) to distinguish between typing-intensive applications like Word, Outlook and Messenger. For example, it may be possible to monitor the frequency of specific keys (e.g. the return/enter key) or combinations of keys (e.g. : + ) to create ☺) within Messenger.

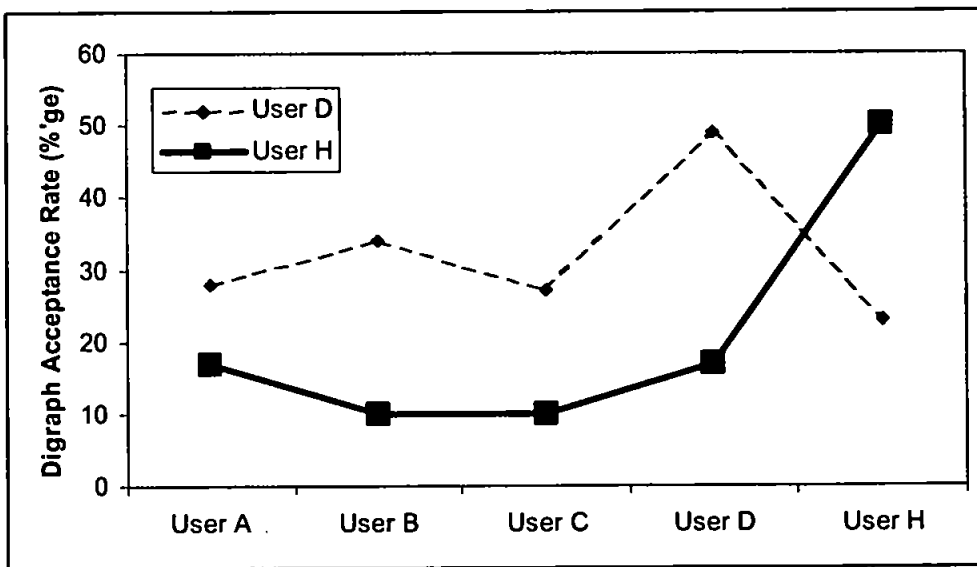


Figure 6.19 - Acceptance rate for two user profiles using Internet Explorer

In Figure 6.19, two users' profiles (users D and H when using Internet Explorer) are examined, showing there is a clear difference between other users' keystroke data (impostors) with appropriate peaks in acceptance rate for the valid users.

While the results shown do not indicate a suitably discriminative metric upon which to base a satisfactory authentication judgement, they do show a level of correlation between a user's typing patterns in an application-specific context. These preliminary results therefore suggest that further work is needed to investigate the use of application-specific keystroke analysis.

## **6.9 Conclusions**

It is clear from the results presented in this chapter that there is potential for continuous user authentication based upon keystroke analysis. However, it is also clear that while the analytical approach provides a level of correlation between reference profile and raw data, the quantity (and range) of raw keylogger data is insufficient to draw any positive findings. The DM approach was limited due to the nature and volume of the data gathered, and is worthy of further investigation (discussed in chapter 9).

Following the findings of this trial, a more comprehensive experiment commenced in November 2003 with more users being profiled over a similar period of time. The next chapter describes the nature of this further trial, and investigates the usefulness of monitoring both trigraph keystroke combinations (timings for three consecutive keystrokes) and word-graph timings (timings for frequently occurring words).

## **Chapter 7**

### ***A Long-Term Trial of Keystroke Analysis***



## **7.1 Introduction**

The previous chapter described an experiment evaluating keystroke analysis based upon inter-keystroke digraph latencies under Windows. Although the trial results demonstrated the viability of this method, the results showed that reliable authentication would need user profiles to be based upon much larger sample sizes. The previous trial was also based on a limited number of users in order to quickly evaluate the viability of the technique.

This chapter presents the results of a large-scale trial that was aimed at evaluating a range of techniques using a larger number of participants.

## **7.2 Experiment Overview**

The first trial concentrated upon the capture and subsequent analysis of digraph latencies and focussed upon inter-keystroke timings. Additionally, contextual information was also stored to allow a preliminary analysis of application-specific keystroke analysis to be conducted. This trial captured and evaluated trigraph and keyword latencies in addition to digraph timings.

7.2.1 Keylogger implementation

The method of keylogging was basically the same as used in the earlier trial with appropriate modification to allow for the logging of trigraphs and keyword latencies (illustrated in Figure 7.1).

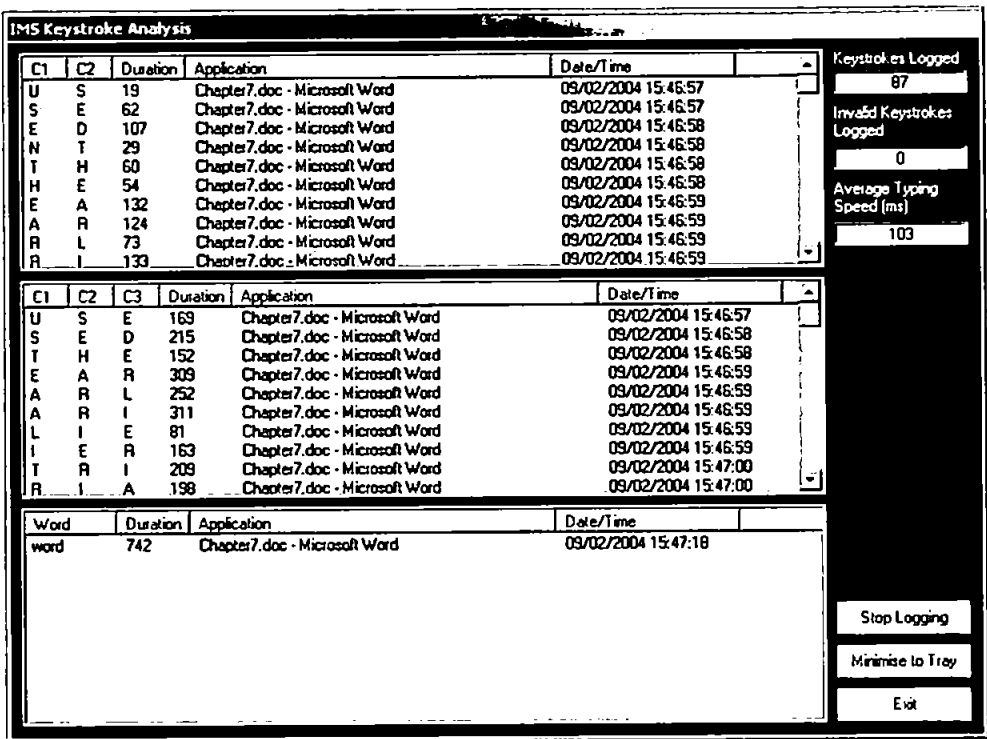


Figure 7.1 - Advanced keylogger

Due to the increased volume of information expected during this trial, the data was logged to an Access database installed as part of the key-logging software (this allowed faster, more flexible extraction of data for the analysis stage). For each digraph pair logged, the application stored six items of information – these being written to the Access database after every 500 digraphs (Table 7.1). This process was also repeated for each trigraph and keyword latency (i.e. trigraphs were stored as three consecutive characters and keywords

as a string as shown in Table 7.2). As can be seen from these examples, significant quantities of data were stored for later analysis.

| Item                 | Data types                                                                                                                                 |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| AutoID               | Auto-incrementing record number. This is used to maintain the order of the keystrokes typed as the timestamp is only accurate to 1 second. |
| Left character (C1)  | ASCII code representing character                                                                                                          |
| Right character (C2) | ASCII code representing character                                                                                                          |
| Latency              | Integer representing inter-keystroke latency in milliseconds                                                                               |
| Application          | String containing the window title from the foreground application.                                                                        |
| Timestamp            | A timestamp is added to every keystroke logged for later use.                                                                              |

Table 7.1 - Keylogger attributes logged per digraph

| Metric   | Example |      |          |          |                                      |                             |                     |
|----------|---------|------|----------|----------|--------------------------------------|-----------------------------|---------------------|
| Digraph  | AutoID  | C1   | C2       | Duration | Application                          | TimeStamp                   |                     |
|          | 1796    | C    | T        | 136      | Google - Microsoft Internet Explorer | 11/06/2003 16:12:04         |                     |
|          | 1797    | T    | I        | 224      | Google - Microsoft Internet Explorer | 11/06/2003 16:12:05         |                     |
|          | 1798    | I    | V        | 179      | Google - Microsoft Internet Explorer | 11/06/2003 16:12:05         |                     |
|          | 1799    | V    | E        | 50       | Google - Microsoft Internet Explorer | 11/06/2003 16:12:05         |                     |
| Trigraph | AutoID  | C1   | C2       | C3       | Duration                             | Application                 | TimeStamp           |
|          | 25461   | R    | E        | S        | 269                                  | Document20 - Microsoft Word | 26/11/2003 15:57:49 |
|          | 25462   | E    | S        | E        | 301                                  | Document20 - Microsoft Word | 26/11/2003 15:57:49 |
|          | 25463   | A    | R        | C        | 472                                  | Document20 - Microsoft Word | 26/11/2003 15:57:51 |
| Keyword  | AutoID  | Word | Duration |          | Application                          | TimeStamp                   |                     |
|          | 241     | that | 314      |          | RE: - Message - Microsoft Word       | 11/10/2003 13:13:39         |                     |
|          | 242     | here | 457      |          | RE: - Message - Microsoft Word       | 11/10/2003 13:13:43         |                     |
|          | 243     | need | 460      |          | RE: - Message - Microsoft Word       | 11/10/2003 13:14:04         |                     |

Table 7.2 - Example keystroke log entries

While digraph and trigraph logging were based upon all keystrokes entered, keyword logging was based on a look up list. The top 200 commonly occurring words in the English language (based on the lexicon provided by the Oxford English Dictionary) were stored in the database file, and as each word was entered, its latency was recorded (the

complete word list can be found in Appendix C). The list used by the keylogger contained a small number of additional keywords for later investigation e.g. usernames and passwords that have been removed from the list presented in the appendix for confidentiality.

### **7.2.2 Filtering**

As with the first trial, extreme short/long digraph latencies that could adversely affect the distribution of digraph times were excluded from the log files. In the first trial the range was restricted to 40ms – 750ms (i.e. any digraph pair whose latency fell outside a nominal range). Unfortunately, the low pass filter was responsible for substantial quantities of data being removed from the user profiles and, as such, was reduced to 10ms for the purposes of this trial. If a digraph was removed due to the filtering, this also reset the trigraph and keyword logging so no further thresholds were needed for these two measures.

## **7.3 Trial Participants**

For this experiment a total of 35 users were profiled over a period of three months. The trial participants were drawn from students and staff in the Network Research Group, the Department of Psychology and two external companies; TMA Global and John Nichols Builders Limited. As with the previous trial, several users disabled the keylogger when entering sensitive information and consequently forgot to re-enable it. Despite this, the key-logging trial collected considerable volumes of data with nearly six million samples collected across digraphs, trigraphs and keywords (Table 7.3). There was again considerable variation in the sample sizes with the smallest digraph log file of 15,951 samples and the largest with 353,867 samples.

| User          | Mean Digraph Latency (ms) | Typing Skill Classification | Digraphs         | Trigraphs        | Words          |
|---------------|---------------------------|-----------------------------|------------------|------------------|----------------|
| User 1        | 91                        | Best                        | 34352            | 23352            | 1403           |
| User 2        | 156                       | Average (skilled)           | 53306            | 36912            | 2599           |
| User 3        | 99                        | Best                        | 156718           | 107107           | 6154           |
| User 4        | 251                       | Average (non-skilled)       | 27324            | 18688            | 1310           |
| User 5        | 112                       | Good                        | 50822            | 36713            | 1465           |
| User 6        | 154                       | Average (skilled)           | 50167            | 34484            | 1885           |
| User 7        | 106                       | Good                        | 78579            | 54959            | 4349           |
| User 8        | 130                       | Good                        | 50102            | 35102            | 2932           |
| User 9        | 97                        | Best                        | 37618            | 24755            | 1741           |
| User 10       | 145                       | Average (skilled)           | 70337            | 48942            | 4643           |
| User 11       | 147                       | Average (skilled)           | 227660           | 145846           | 10617          |
| User 12       | 102                       | Good                        | 20216            | 14142            | 1032           |
| User 13       | 157                       | Average (skilled)           | 65312            | 43015            | 1730           |
| User 14       | 141                       | Average (skilled)           | 33639            | 23090            | 1784           |
| User 15       | 139                       | Good                        | 15951            | 11159            | 1068           |
| User 16       | 150                       | Average (skilled)           | 42839            | 30299            | 2037           |
| User 17       | 106                       | Good                        | 105543           | 68068            | 3173           |
| User 18       | 177                       | Average (skilled)           | 89730            | 59292            | 3121           |
| User 19       | 117                       | Good                        | 103876           | 71635            | 4617           |
| User 20       | 121                       | Good                        | 78597            | 53495            | 4479           |
| User 21       | 141                       | Average (skilled)           | 80626            | 55881            | 2807           |
| User 22       | 110                       | Good                        | 117365           | 79534            | 6557           |
| User 23       | 131                       | Good                        | 118805           | 77013            | 5682           |
| User 24       | 89                        | Best                        | 201260           | 131954           | 8517           |
| User 25       | 203                       | Average (skilled)           | 38944            | 26655            | 2266           |
| User 26       | 192                       | Average (skilled)           | 48469            | 33907            | 2555           |
| User 27       | 125                       | Good                        | 33068            | 23115            | 1679           |
| User 28       | 91                        | Best                        | 70217            | 47033            | 2128           |
| User 29       | 104                       | Good                        | 88059            | 55707            | 3815           |
| User 30       | 202                       | Average (skilled)           | 40741            | 28789            | 1007           |
| User 31       | 86                        | Best                        | 310823           | 211419           | 19726          |
| User 32       | 93                        | Best                        | 353867           | 237274           | 18056          |
| User 33       | 144                       | Average (skilled)           | 276669           | 183455           | 6057           |
| User 34       | 143                       | Average (skilled)           | 124409           | 87079            | 953            |
| User 35       | 130                       | Good                        | 140044           | 85413            | 6240           |
| <b>Totals</b> |                           |                             | <b>3,436,054</b> | <b>2,305,283</b> | <b>150,184</b> |

Table 7.3 - Participant typing skill

Before considering the data from each user, the typing skill for each participant was evaluated based on the categorisations proposed by Card et al. (1980), where typists are broadly categorised into one of five categories (Table 7.4). These results are also presented in Table 7.3 and presented graphically in Figure 7.2. The results are weighted towards typists with above average skills due to the nature of the test subjects (i.e. all

subjects were regular computer users who spent prolonged periods typing). This was considered acceptable as the likely use for a fully implemented system would be in environments with semi-skilled users (i.e. relatively few unskilled typists).

| Category                                | Average Keystroke Interval (Seconds) |
|-----------------------------------------|--------------------------------------|
| Best typist (135wpm)                    | 0.08                                 |
| Good typist (90wpm)                     | 0.12                                 |
| Average skilled typist (55wpm)          | 0.20                                 |
| Average non-skilled typist (40wpm)      | 0.28                                 |
| Worst typist – unfamiliar with keyboard | 1.20                                 |

Table 7.4 - Classification of typist skill (Card et al. 1980)

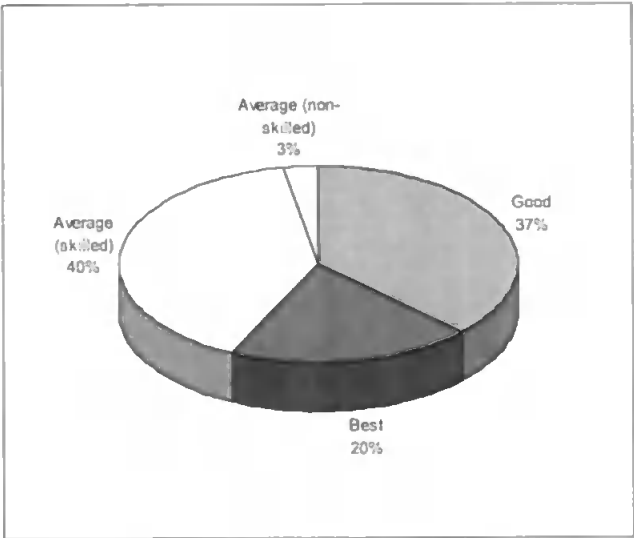


Figure 7.2 - Participant typing skills

The trial results presented in this chapter were based upon all 35 users (unlike the previous trial that had to eliminate three users due to small sample sizes). It is interesting to note that the relationship between the volume of data obtained and the False Acceptance Rate is not as might first be expected. If we consider Figure 7.3, it would be reasonable to assume that the relationship would be linear; i.e. as the number of samples increased, the FAR should decrease (as the system is able to construct better profiles). However, the figure indicates that there is no direct relationship between these two variables. This can be

assumed to indicate a stronger relationship between the user and the acceptance rate rather than the acceptance rate and the volume of data logged (i.e. simply having large volumes of data is not guaranteed to provide a lower false acceptance rate).

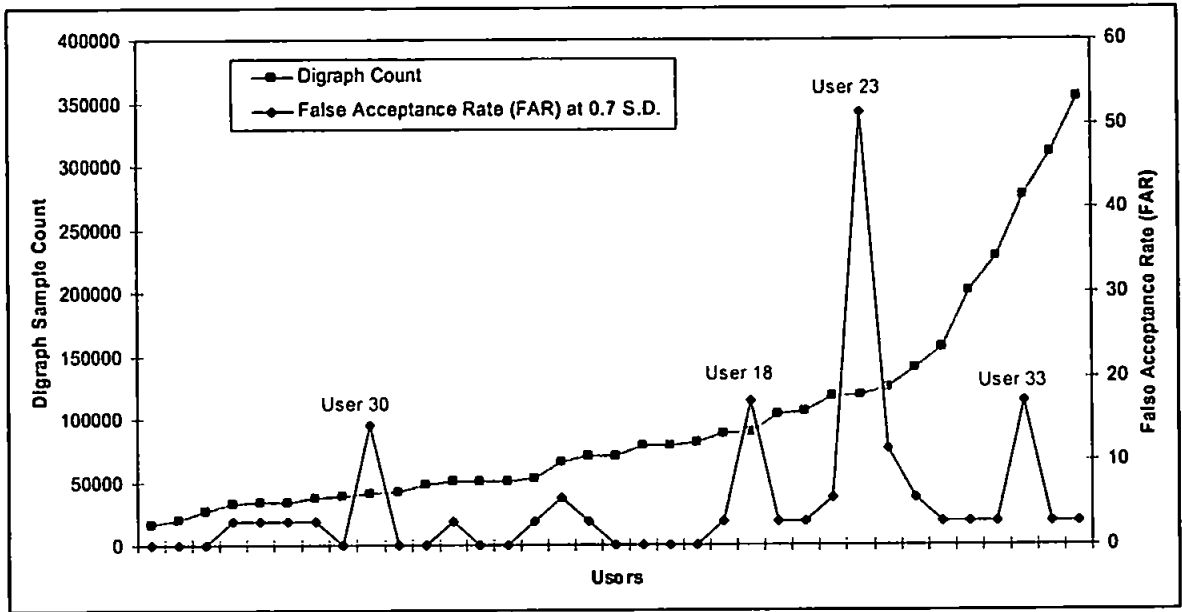


Figure 7.3 - Relationship between keylogger sample size and digraph FAR at 0.7 standard deviations

The results illustrated in Figure 7.3 show four users for whom high false acceptance rates are encountered. The results presented in this chapter (and in chapter 8) show that these users consistently produce higher FAR rates than other users – this is demonstrated later in this chapter when these users are removed and the results recalculated.

If we consider the deviation of a users' own typing, the standard deviation from the mean digraph latency is used to show the overall variance in a user's typing profile. The results from the trial participants are shown in Figure 7.4, which show significant variation across the users – effectively showing each users' consistency. The results are ordered by increasing average digraph latency with error bars indicating the standard deviation range

for each user. For reference, an ideal chart is shown in Figure 7.5 which shows a much more even distribution between users (and therefore better distinction between the classes of users). Figure 7.5 is based on the same mean latency with error bars indicating a 0.5 standard deviation from the mean.

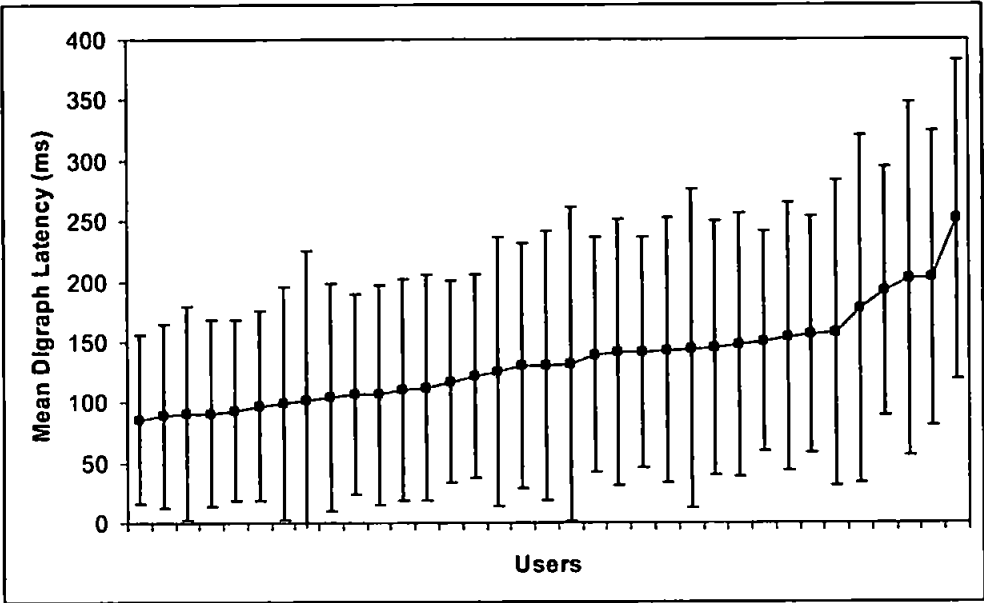


Figure 7.4 - Average digraph latency per user with standard deviation (ordered by mean latency)

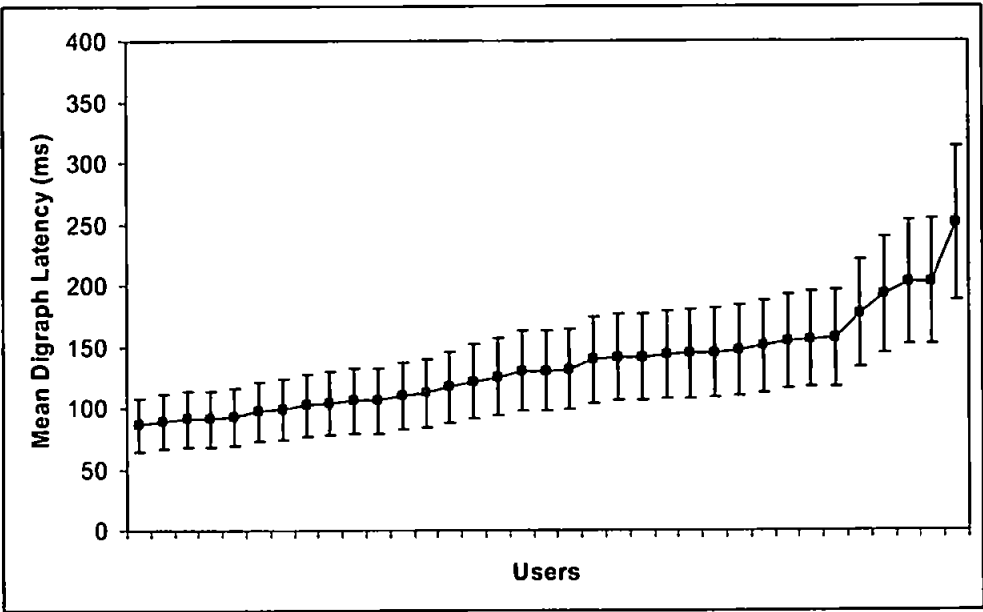


Figure 7.5 - 'Ideal' chart based on Figure 7.4



7.4 Analysis

NB due to the volume of data produced in this study, the body of the thesis, and the accompanying material in appendix C, contain only selected results. The full results can be found on the accompanying CD.

In the previous trial the experimental data for each user was processed off-line to calculate the mean and standard deviation values for each unique digraph pair. This process was again conducted on the captured data from this trial, but was repeated for each stored metric (digraphs, trigraphs and keyword latencies). Due to the volume of data, a profile generating utility was developed in Visual Basic (illustrated in Figure 7.6).

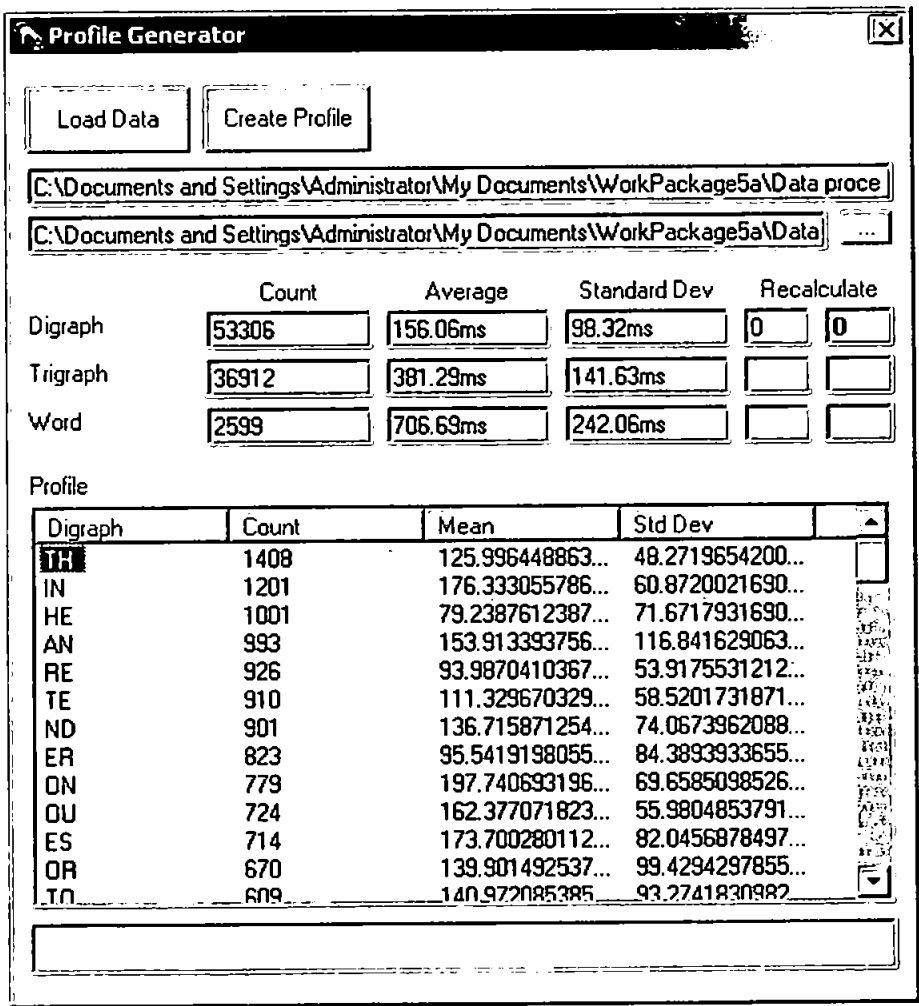


Figure 7.6 - Profile generator

The profile generator ran a series of queries against the original data (digraph, trigraph and keyword), and produced a table of results for each profiled value. For each of these, the count of samples, mean and standard deviation values were calculated and then stored to another Access database (the profile database). This resulted in a single database file containing 105 reference profiles (one each digraph, trigraph and keyword profile for each user – 3 x 35). As with the previous trial, in cases where the standard deviation was greater than the mean, the dataset was reduced by 10% to tighten the distribution. In a small number of cases (two users) this automatic adjustment did not provide sufficient change in the variance of the calculated values. In these cases, the data was recalculated manually for the problem digraphs. Where a digraph (or trigraph/word) required recalculation, this was shown as a cumulative count in the profile generator. The figure in red indicated the number of digraphs that required manual intervention (a total of eight digraph pairs from two users required this manual procedure – there were no incidents of trigraphs/words requiring manual intervention).

Completed profiles were then compared against the original keylogger files to determine the proportion of logged digraphs that were represented in the user profile. The quantity of unmatched samples (and resulting proportion represented as a percentage) are shown in Table 7.5 and graphically in Figure 7.7 (the results shown in Figure 7.7 are ordered by ascending sampled digraphs). These results show a clear relationship between the size of the raw sampled data (i.e. the number of sampled digraphs) and the proportion of matched digraphs when compared with the generated profile. This is significant as it demonstrates the importance of a substantial volume of keystroke data required to generate a usable profile.

| User    | Total Digraphs | Unmatched | Unmatched Percentage |
|---------|----------------|-----------|----------------------|
| User 1  | 34352          | 20869     | 60.8%                |
| User 2  | 53306          | 17425     | 32.7%                |
| User 3  | 156718         | 17179     | 11.0%                |
| User 4  | 27324          | 15211     | 55.7%                |
| User 5  | 50822          | 18636     | 36.7%                |
| User 6  | 50167          | 17679     | 35.2%                |
| User 7  | 78579          | 15547     | 19.8%                |
| User 8  | 50102          | 18381     | 36.7%                |
| User 9  | 37618          | 18794     | 50.0%                |
| User 10 | 70337          | 15505     | 22.0%                |
| User 11 | 227660         | 13908     | 6.1%                 |
| User 12 | 20216          | 12600     | 62.3%                |
| User 13 | 65312          | 19509     | 29.9%                |
| User 14 | 33639          | 17201     | 51.1%                |
| User 15 | 15951          | 11747     | 73.6%                |
| User 16 | 42839          | 15776     | 36.8%                |
| User 17 | 105543         | 20026     | 19.0%                |
| User 18 | 89730          | 17888     | 19.9%                |
| User 19 | 103876         | 18549     | 17.9%                |
| User 20 | 78597          | 16553     | 21.1%                |
| User 21 | 80626          | 16647     | 20.6%                |
| User 22 | 117365         | 17616     | 15.0%                |
| User 23 | 118805         | 20181     | 17.0%                |
| User 24 | 201260         | 16608     | 8.3%                 |
| User 25 | 38944          | 16997     | 43.6%                |
| User 26 | 48469          | 16321     | 33.7%                |
| User 27 | 33068          | 17817     | 53.9%                |
| User 28 | 70217          | 21064     | 30.0%                |
| User 29 | 88059          | 19817     | 22.5%                |
| User 30 | 40741          | 17569     | 43.1%                |
| User 31 | 310823         | 14563     | 4.7%                 |
| User 32 | 353867         | 14378     | 4.1%                 |
| User 33 | 276669         | 16721     | 6.0%                 |
| User 34 | 124409         | 15696     | 12.6%                |
| User 35 | 140044         | 18066     | 12.9%                |

Table 7.5 - Unmatched captured digraphs

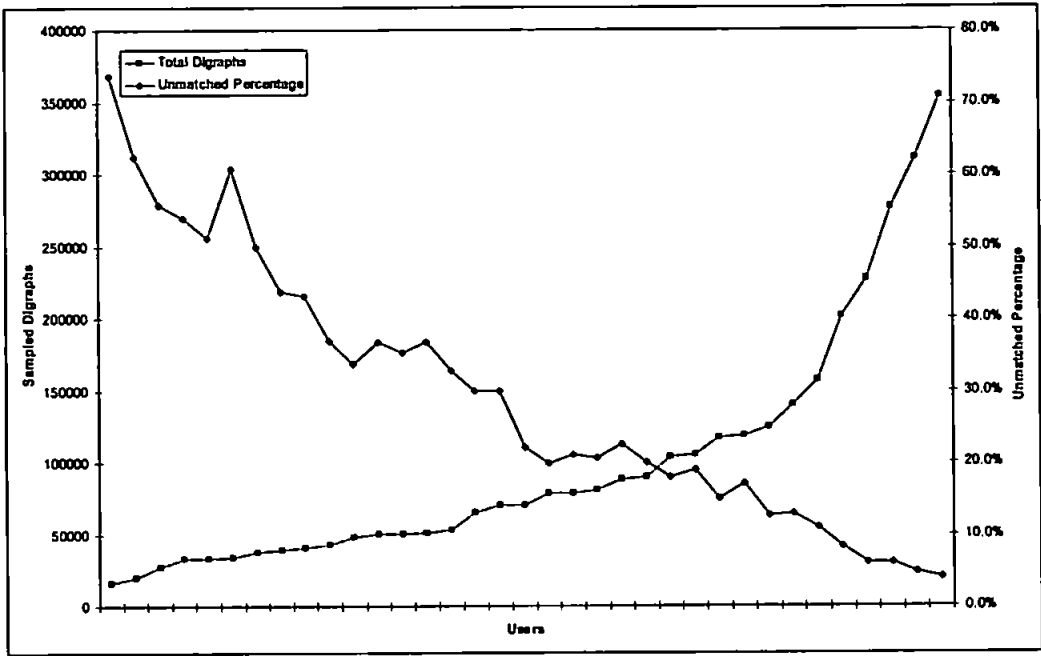


Figure 7.7 - Unmatched digraphs compared with digraph sample size

Once all the user profiles were calculated, the data comparator was used to generate tables of results for each of the methods. The data comparator (Figure 7.8) was based upon the original analyser described in section 6.5 in the previous chapter. A small number of additional features were introduced to the comparator to cater for the inclusion of trigraphs and keyword profiles. Firstly, a series of radio buttons were included to allow the selection of profile metrics (to compare based on digraphs, trigraphs or keywords). Secondly, a check box was added to allow the alert level (as described in the previous chapter) to be increased by unmatched digraphs.

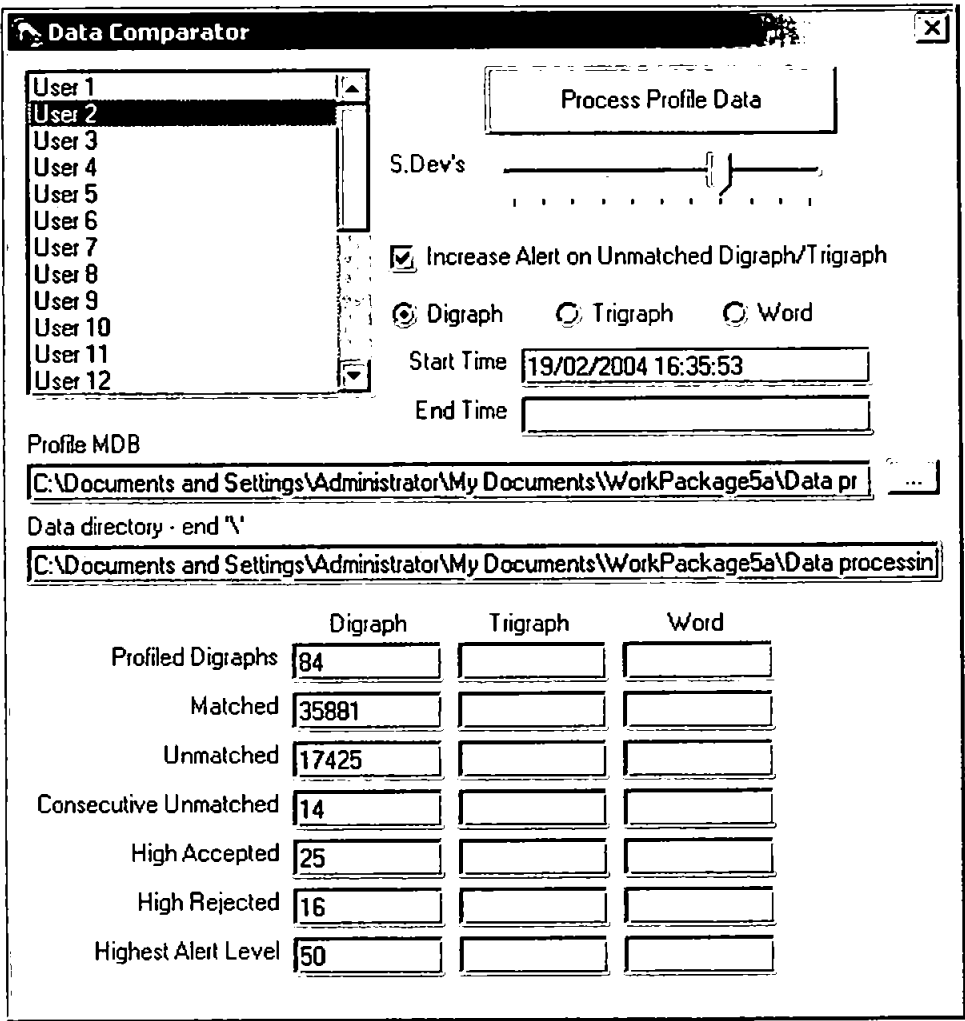


Figure 7.8 - Data comparator

In the previous trial, when a digraph was processed that did not exist in the reference profile, the alert level remained static (simply increasing the count of unmatched digraphs). This trial considered the role of unmatched digraphs as they are a potential indicator of impostor activity – i.e. if a user types a specific digraph pair infrequently (to the extent that there is insufficient data on which to base a profile), it is reasonable to assume that these occurrences are un-representative of that user’s normal typing behaviour. By default, in this trial, an unmatched digraph increases the alert level by one, whilst a matched accepted/rejected digraph pair varies the alert level by two accordingly. This behaviour

can be adjusted by selecting the checkbox – once unchecked, the alert level is not affected by unmatched samples.

Before starting the full profile comparisons a trial comparison was conducted based upon a random selection of five users in order to determine the optimum settings for the deviation threshold. In the previous study the deviation settings were chosen from a range of 0.5, 1.0, 1.5 and 2.0 standard deviations with the best results obtained at 0.5. In order to determine an optimum setting, profile comparisons were made between 0.5 and 1.0 standard deviations (values below 0.5 had already been assessed). For the randomly selected users the best results were obtained at 0.7, with an increase in alert level above and below this threshold. As such, the later comparisons were performed with standard deviations settings of 0.6, 0.7 and 0.8.

Once the profile comparison was started, each users' reference profile was loaded and then compared against the raw keylogger data files for all 35 users. This produced a table of 35 sets of results for each user (i.e. 35 tables each with 35x6 result values). This process was repeated for trigraphs and keywords with the three different profile deviation settings (0.6, 0.7 and 0.8 standard deviations from the mean). It should be noted that a setting of 0.5 standard deviations was introduced to the trigraph and keyword comparisons due to poor performance at 0.6 and 0.7. This provided approximately 125,000 result values. With an average of nearly 100,000 samples per data file, each data comparison took approximately two hours, with a total of 18 comparisons conducted – six for digraph, eight for trigraph and four for keywords (see Table 7.6).

| Metric    | Standard Deviations (S.D.)                                                         |
|-----------|------------------------------------------------------------------------------------|
| Digraphs  | 0.6, 0.7, 0.8 S.D.                                                                 |
| Trigraphs | 0.5, 0.6, 0.7, 0.8 S.D.<br><i>0.5 added due to poor performance at 0.6 and 0.7</i> |
| Keyword   | 0.5, 0.6, 0.7, 0.8 S.D.<br><i>0.5 added due to poor performance at 0.6 and 0.7</i> |

Table 7.6 - Profile comparison settings

| 0.6 S.D. | DIGRAPHS | Reference Profile : |                       |               | User 3        |                     |
|----------|----------|---------------------|-----------------------|---------------|---------------|---------------------|
| User     | Matched  | Unmatched           | Consecutive unmatched | High accepted | High rejected | Highest alert level |
| User 1   | 28143    | 6209                | 65                    | 12            | 18            | 15513               |
| User 2   | 46797    | 6509                | 10                    | 9             | 28            | 42469               |
| User 3   | 139539   | 17179               | 11                    | 17            | 14            | 72                  |
| User 4   | 24234    | 3090                | 15                    | 6             | 40            | 32450               |
| User 5   | 42111    | 8711                | 23                    | 12            | 32            | 21713               |
| User 6   | 43399    | 6768                | 16                    | 14            | 29            | 36460               |
| User 7   | 69491    | 9088                | 10                    | 14            | 18            | 29808               |
| User 8   | 44356    | 5746                | 9                     | 10            | 28            | 30932               |
| User 9   | 31808    | 5810                | 87                    | 11            | 18            | 14980               |
| User 10  | 62110    | 8227                | 6                     | 8             | 29            | 49329               |
| User 11  | 194687   | 32973               | 29                    | 13            | 32            | 165327              |
| User 12  | 17574    | 2642                | 6                     | 8             | 32            | 20580               |
| User 13  | 53395    | 11917               | 95                    | 19            | 32            | 54845               |
| User 14  | 29885    | 3754                | 7                     | 10            | 21            | 22528               |
| User 15  | 14037    | 1914                | 6                     | 9             | 21            | 9774                |
| User 16  | 36891    | 5948                | 7                     | 11            | 38            | 32348               |
| User 17  | 87249    | 18294               | 14                    | 18            | 25            | 36618               |
| User 18  | 78351    | 11379               | 10                    | 11            | 34            | 65447               |
| User 19  | 89323    | 14553               | 28                    | 11            | 49            | 42925               |
| User 20  | 68617    | 9980                | 10                    | 11            | 48            | 41558               |
| User 21  | 70145    | 10481               | 24                    | 10            | 26            | 61197               |
| User 22  | 100206   | 17159               | 22                    | 14            | 21            | 45379               |
| User 23  | 97646    | 21159               | 45                    | 12            | 24            | 70889               |
| User 24  | 169445   | 31815               | 16                    | 16            | 22            | 56372               |
| User 25  | 33843    | 5101                | 6                     | 7             | 38            | 45697               |
| User 26  | 42281    | 6188                | 6                     | 6             | 38            | 54008               |
| User 27  | 28297    | 4771                | 10                    | 13            | 15            | 10809               |
| User 28  | 60018    | 10199               | 19                    | 14            | 16            | 10513               |
| User 29  | 75695    | 12364               | 13                    | 13            | 34            | 31960               |
| User 30  | 34376    | 6365                | 24                    | 13            | 51            | 37715               |
| User 31  | 269989   | 40834               | 48                    | 17            | 23            | 5486                |
| User 32  | 304826   | 49041               | 29                    | 15            | 23            | 150798              |
| User 33  | 216573   | 60096               | 31                    | 11            | 40            | 197230              |
| User 34  | 100837   | 23572               | 25                    | 20            | 28            | 94940               |
| User 35  | 117220   | 22824               | 48                    | 14            | 26            | 61550               |

Table 7.7 - Sample output file

Once the profile comparison was completed, the results were exported to an Excel spreadsheet (an example is shown in Table 7.7). In this table, the highlighted result line indicates the comparison between user 3's raw keylogger data and their generated reference profile with the other rows indicating the comparison of other users (i.e. impostors) compared against the reference profile (user 3). The spreadsheets contained a number of functions to derive 2-dimensional tables of data from the raw results from the comparator (Table 7.8) from which the FAR/FRR figures could be derived.

|         | User 1 | User 2 | User n | User 35 |
|---------|--------|--------|--------|---------|
| User 1  | 54     | 39186  | 15513  | 57030   |
| User 2  | 16277  | 54     | 42469  | 112493  |
| User n  | 51355  | 27329  | 72     | 44405   |
| User 35 | 58229  | 91420  | 21713  | 50      |

Table 7.8 - Combined results showing highest alert levels

Following the basic analysis described in this section, a further modification was made to the comparator to determine how many keystrokes were needed before either the valid user was challenged or an impostor detected. The threshold for this challenge was based upon the best performance thresholds from the earlier trials and was initially set at an alert level of 70. The results from this trial using the digraph keylogger files at a threshold of 0.7 standard deviations are presented in Table 7.9. The results from this trial were somewhat variable, while some users had good results (e.g. users 7, 10 and 26), most user profiles had only moderately successful results. If we consider user 2, while 29/34 (85%) impostors were challenged in less than 100 digraphs, user 16 (when acting as an impostor against user 2's reference profile) was able to type over 40,000 digraphs before being challenged.



| Reference Profiles |    |    | User 1 | User 2 | User 3 | User 4 | User 5 | User 6 | User 7 | User 8 | User 9 | User 10 | User 11 | User 12 | User 13 | User 14 | User 15 | User 16 | User 17 | User 18 | User 19 | User 20 | User 21 | User 22 | User 23 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 30 | User 31 | User 32 | User 33 | User 34 | User 35 |
|--------------------|----|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| User 1             | 56 | 21 | 72     | 22     | 22     | 22     | 22     | 22     | 22     | 22     | 22     | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      |
| User 2             | 53 | 20 | 70     | 21     | 21     | 21     | 21     | 21     | 21     | 21     | 21     | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      | 21      |
| User 3             | 51 | 20 | 68     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 4             | 50 | 20 | 67     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 5             | 49 | 20 | 66     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 6             | 48 | 20 | 65     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 7             | 47 | 20 | 64     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 8             | 46 | 20 | 63     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 9             | 45 | 20 | 62     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 10            | 44 | 20 | 61     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 11            | 43 | 20 | 60     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 12            | 42 | 20 | 59     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 13            | 41 | 20 | 58     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 14            | 40 | 20 | 57     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 15            | 39 | 20 | 56     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 16            | 38 | 20 | 55     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 17            | 37 | 20 | 54     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 18            | 36 | 20 | 53     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 19            | 35 | 20 | 52     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 20            | 34 | 20 | 51     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 21            | 33 | 20 | 50     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 22            | 32 | 20 | 49     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 23            | 31 | 20 | 48     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 24            | 30 | 20 | 47     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 25            | 29 | 20 | 46     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 26            | 28 | 20 | 45     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 27            | 27 | 20 | 44     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 28            | 26 | 20 | 43     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 29            | 25 | 20 | 42     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 30            | 24 | 20 | 41     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 31            | 23 | 20 | 40     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 32            | 22 | 20 | 39     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 33            | 21 | 20 | 38     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 34            | 20 | 20 | 37     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |
| User 35            | 19 | 20 | 36     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20     | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |

Table 7.9 - Number of keypresses before a challenge

The results in Table 7.9 can also be considered in terms of the average number of keystrokes required before a challenge is issued. The results show that an average of 6,390 digraphs were accepted before an impostor was challenged compared with an average of 68,755 digraphs before the valid user was challenged. While these results seem to provide the appropriate differentiation between impostor and valid user, giving an impostor the opportunity to type over 6,000 digraphs presents a major security risk. This figure is reduced to 4,300 digraphs if the users identified in Figure 7.3 are removed (i.e. the users for whom keystroke analysis is shown to be unworkable).

For this trial the False Rejection Rate (FRR) was fixed at 0% (i.e. the valid user would not have been rejected by the system). The False Acceptance Rates (FAR) were calculated for each user at the deviation thresholds specified in Table 7.6 and are shown in Table 7.10.

When the results were calculated, the False Acceptance Rates per user were averaged across all users to provide an average FAR for each metric. The averaged results for this approach are shown in Table 7.11. It should be noted that the keyword latencies did not use the unmatched alert increase due to the use of a word list/dictionary. It was not appropriate to include an unmatched alert increase as the system is designed to monitor specific word occurrences unlike the digraph/trigraph approach that monitors all possible combinations – i.e. only words that are being monitored would actually be logged.

|                    | Digraph FAR |      |      |      |      |      | Trigraph FAR |      |      |      |      |      |      |      | Keyword FAR |      |      |      |
|--------------------|-------------|------|------|------|------|------|--------------|------|------|------|------|------|------|------|-------------|------|------|------|
| Standard Deviation | 0.6         |      | 0.7  |      | 0.8  |      | 0.5          |      | 0.6  |      | 0.7  |      | 0.8  |      | 0.5         | 0.6  | 0.7  | 0.8  |
| Unmatched Alert    | N           | Y    | N    | Y    | N    | Y    | N            | Y    | N    | Y    | N    | Y    | N    | Y    | N           | N    | N    | N    |
| User 1             | 2.9         | 2.9  | 2.9  | 8.6  | 2.9  | 8.6  | 8.6          | 17.1 | 8.6  | 8.6  | 8.6  | 25.7 | 8.6  | 31.4 | 97.1        | 97.1 | 91.4 | 91.4 |
| User 2             | 0.0         | 2.9  | 2.9  | 5.7  | 2.9  | 11.4 | 34.3         | 0.0  | 34.3 | 34.3 | 34.3 | 5.7  | 31.4 | 8.6  | 2.9         | 2.9  | 2.9  | 5.7  |
| User 3             | 0.0         | 0.0  | 2.9  | 5.7  | 5.7  | 11.4 | 74.3         | 5.7  | 62.9 | 62.9 | 54.3 | 20.0 | 40.0 | 25.7 | 0.0         | 8.6  | 20.0 | 28.6 |
| User 4             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 2.9  | 5.7          | 0.0  | 5.7  | 5.7  | 5.7  | 0.0  | 5.7  | 0.0  | 5.7         | 0.0  | 0.0  | 0.0  |
| User 5             | 0.0         | 0.0  | 0.0  | 8.6  | 0.0  | 11.4 | 28.6         | 2.9  | 28.6 | 28.6 | 28.6 | 14.3 | 28.6 | 22.9 | 8.6         | 11.4 | 14.3 | 20.0 |
| User 6             | 0.0         | 2.9  | 0.0  | 8.6  | 0.0  | 22.9 | 28.6         | 2.9  | 28.6 | 28.6 | 28.6 | 5.7  | 25.7 | 11.4 | 34.3        | 11.4 | 2.9  | 8.6  |
| User 7             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 2.9  | 34.3         | 0.0  | 28.6 | 28.6 | 25.7 | 0.0  | 20.0 | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  |
| User 8             | 11.4        | 5.7  | 2.9  | 5.7  | 2.9  | 40.0 | 28.6         | 17.1 | 28.6 | 28.6 | 25.7 | 28.6 | 25.7 | 37.1 | 0.0         | 0.0  | 2.9  | 8.6  |
| User 9             | 2.9         | 2.9  | 2.9  | 0.0  | 0.0  | 14.3 | 17.1         | 5.7  | 17.1 | 17.1 | 17.1 | 11.4 | 14.3 | 20.0 | 22.9        | 25.7 | 34.3 | 34.3 |
| User 10            | 0.0         | 0.0  | 0.0  | 8.6  | 2.9  | 14.3 | 37.1         | 0.0  | 31.4 | 31.4 | 28.6 | 2.9  | 22.9 | 8.6  | 2.9         | 0.0  | 0.0  | 0.0  |
| User 11            | 0.0         | 0.0  | 2.9  | 14.3 | 17.1 | 22.9 | 82.9         | 2.9  | 65.7 | 65.7 | 51.4 | 0.0  | 11.4 | 11.4 | 37.1        | 5.7  | 2.9  | 28.6 |
| User 12            | 0.0         | 5.7  | 0.0  | 5.7  | 0.0  | 14.3 | 2.9          | 14.3 | 2.9  | 2.9  | 2.9  | 22.9 | 2.9  | 28.6 | 22.9        | 25.7 | 31.4 | 40.0 |
| User 13            | 8.6         | 11.4 | 5.7  | 11.4 | 14.3 | 11.4 | 40.0         | 2.9  | 40.0 | 40.0 | 37.1 | 11.4 | 37.1 | 11.4 | 8.6         | 8.6  | 11.4 | 14.3 |
| User 14            | 2.9         | 2.9  | 2.9  | 8.6  | 0.0  | 34.3 | 8.6          | 8.6  | 8.6  | 8.6  | 8.6  | 22.9 | 5.7  | 28.6 | 0.0         | 2.9  | 5.7  | 5.7  |
| User 15            | 0.0         | 0.0  | 0.0  | 2.9  | 0.0  | 8.6  | 0.0          | 14.3 | 0.0  | 0.0  | 0.0  | 17.1 | 0.0  | 20.0 | 22.9        | 17.1 | 25.7 | 25.7 |
| User 16            | 0.0         | 5.7  | 0.0  | 2.9  | 0.0  | 5.7  | 22.9         | 0.0  | 20.0 | 20.0 | 14.3 | 2.9  | 14.3 | 5.7  | 0.0         | 0.0  | 2.9  | 14.3 |
| User 17            | 0.0         | 0.0  | 2.9  | 11.4 | 14.3 | 25.7 | 48.6         | 2.9  | 48.6 | 48.6 | 45.7 | 8.6  | 40.0 | 11.4 | 5.7         | 5.7  | 5.7  | 11.4 |
| User 18            | 8.6         | 11.4 | 17.1 | 8.6  | 17.1 | 25.7 | 48.6         | 17.1 | 42.9 | 42.9 | 40.0 | 0.0  | 37.1 | 5.7  | 28.6        | 8.6  | 11.4 | 17.1 |
| User 19            | 0.0         | 2.9  | 2.9  | 5.7  | 2.9  | 8.6  | 65.7         | 0.0  | 62.9 | 62.9 | 62.9 | 8.6  | 62.9 | 11.4 | 5.7         | 14.3 | 20.0 | 17.1 |
| User 20            | 0.0         | 0.0  | 0.0  | 5.7  | 5.7  | 22.9 | 42.9         | 0.0  | 40.0 | 40.0 | 31.4 | 5.7  | 28.6 | 8.6  | 0.0         | 2.9  | 2.9  | 5.7  |
| User 21            | 0.0         | 0.0  | 0.0  | 0.0  | 2.9  | 2.9  | 40.0         | 0.0  | 28.6 | 28.6 | 17.1 | 2.9  | 5.7  | 2.9  | 0.0         | 2.9  | 5.7  | 8.6  |
| User 22            | 2.9         | 8.6  | 5.7  | 8.6  | 8.6  | 25.7 | 65.7         | 0.0  | 57.1 | 57.1 | 45.7 | 5.7  | 31.4 | 17.1 | 0.0         | 5.7  | 5.7  | 11.4 |
| User 23            | 68.6        | 54.3 | 51.4 | 62.9 | 60.0 | 80.0 | 71.4         | 45.7 | 71.4 | 71.4 | 68.6 | 34.3 | 68.6 | 45.7 | 37.1        | 37.1 | 45.7 | 45.7 |
| User 24            | 2.9         | 0.0  | 2.9  | 5.7  | 5.7  | 8.6  | 62.9         | 2.9  | 54.3 | 54.3 | 25.7 | 14.3 | 14.3 | 28.6 | 0.0         | 2.9  | 8.6  | 14.3 |
| User 25            | 0.0         | 2.9  | 0.0  | 2.9  | 0.0  | 14.3 | 14.3         | 0.0  | 8.6  | 8.6  | 8.6  | 2.9  | 8.6  | 0.0  | 2.9         | 0.0  | 0.0  | 0.0  |
| User 26            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 5.7  | 22.9         | 0.0  | 22.9 | 22.9 | 20.0 | 0.0  | 17.1 | 0.0  | 5.7         | 0.0  | 0.0  | 5.7  |
| User 27            | 2.9         | 2.9  | 2.9  | 17.1 | 2.9  | 48.6 | 11.4         | 11.4 | 11.4 | 11.4 | 11.4 | 28.6 | 11.4 | 45.7 | 8.6         | 2.9  | 5.7  | 5.7  |
| User 28            | 2.9         | 2.9  | 2.9  | 5.7  | 2.9  | 17.1 | 42.9         | 8.6  | 42.9 | 42.9 | 42.9 | 17.1 | 42.9 | 14.3 | 8.6         | 17.1 | 28.6 | 37.1 |
| User 29            | 5.7         | 5.7  | 2.9  | 22.9 | 20.0 | 48.6 | 48.6         | 11.4 | 42.9 | 42.9 | 42.9 | 20.0 | 42.9 | 22.9 | 11.4        | 8.6  | 14.3 | 31.4 |
| User 30            | 14.3        | 8.6  | 14.3 | 14.3 | 11.4 | 20.0 | 22.9         | 20.0 | 22.9 | 22.9 | 22.9 | 22.9 | 20.0 | 37.1 | 45.7        | 28.6 | 28.6 | 8.6  |
| User 31            | 0.0         | 0.0  | 2.9  | 2.9  | 5.7  | 8.6  | 0.0          | 0.0  | 0.0  | 0.0  | 0.0  | 2.9  | 0.0  | 5.7  | 0.0         | 0.0  | 2.9  | 5.7  |
| User 32            | 0.0         | 0.0  | 2.9  | 8.6  | 11.4 | 20.0 | 54.3         | 0.0  | 0.0  | 0.0  | 0.0  | 8.6  | 0.0  | 14.3 | 2.9         | 5.7  | 14.3 | 14.3 |
| User 33            | 17.1        | 14.3 | 17.1 | 14.3 | 22.9 | 28.6 | 88.6         | 77.1 | 82.9 | 82.9 | 65.7 | 54.3 | 57.1 | 71.4 | 80.0        | 68.6 | 20.0 | 28.6 |
| User 34            | 5.7         | 2.9  | 11.4 | 14.3 | 14.3 | 14.3 | 80.0         | 0.0  | 48.6 | 48.6 | 42.9 | 0.0  | 37.1 | 2.9  | 97.1        | 97.1 | 97.1 | 97.1 |
| User 35            | 22.9        | 14.3 | 5.7  | 34.3 | 25.7 | 54.3 | 71.4         | 25.7 | 65.7 | 65.7 | 65.7 | 25.7 | 62.9 | 45.7 | 34.3        | 5.7  | 11.4 | 14.3 |
| Average            | 5.2         | 5.0  | 4.9  | 9.8  | 8.1  | 20.5 | 38.2         | 9.1  | 33.3 | 33.3 | 29.5 | 13.0 | 25.2 | 18.9 | 18.3        | 15.2 | 16.5 | 20.2 |

Table 7.10 - Results from single-metric measures

| Metric    | S.D. | Unmatched Alert | FAR   |
|-----------|------|-----------------|-------|
| Digraphs  | 0.6  | No              | 5.2%  |
|           | 0.6  | Yes             | 5.0%  |
|           | 0.7  | No              | 4.9%  |
|           | 0.7  | Yes             | 9.8%  |
|           | 0.8  | No              | 8.1%  |
|           | 0.8  | Yes             | 20.5% |
| Trigraphs | 0.5  | No              | 38.2% |
|           | 0.5  | Yes             | 9.1%  |
|           | 0.6  | No              | 33.3% |
|           | 0.6  | Yes             | 33.3% |
|           | 0.7  | No              | 29.5% |
|           | 0.7  | Yes             | 13.0% |
|           | 0.8  | No              | 25.2% |
|           | 0.8  | Yes             | 18.9% |
| Words     | 0.5  | No              | 18.3% |
|           | 0.6  | No              | 15.2% |
|           | 0.7  | No              | 16.5% |
|           | 0.8  | No              | 20.2% |

Table 7.11 - Final results

While the results shown in Table 7.11 show some encouraging FAR levels there is still significant variation with the best results obtained at 0.7 standard deviations for digraphs, 0.5 standard deviations for trigraphs (with increased alert levels for unmatched digraphs) and 0.6 for keywords. However, when the full results are considered (as shown in Table 7.10), even at the optimum settings, certain users show high FAR levels (e.g. user 23's profile returned FAR levels of 51.4%, 45.7% and 37.1% respectively for digraph, trigraph and keywords at the optimum settings). It can also be clearly observed that the results for trigraphs and keywords are significantly worse when compared with those for digraphs – this is most likely to be related to the number of underlying samples used for these techniques (i.e. the number of sampled digraphs were significantly higher than that for trigraphs and keywords, with a corresponding increase of samples per digraph). It is probable that over a longer period of time, the profiles could be refined for trigraphs and

keywords to produce a more distinct user profile with a corresponding reduction in the FAR.

These results also demonstrate that the techniques can be very effective for some users while very ineffective for others. For example, when considering digraph FAR's at 0.6 standard deviations (where 0% FAR was actually experienced for 19 out of the 35 users – 54.3%) the average FAR (5.2%) has been heavily influenced by a single user (user 23), whose 68.6% FAR dramatically increases the average. In a full implementation, it would be likely that the use of keystroke analysis would only form a part of a comprehensive user monitoring system. As such, a users' typing would only be monitored if the method was shown to be a discriminating authentication technique for that user. The removal of user 23 from the results in Table 7.10 significantly affects the average FAR's presented in Table 7.11, reducing the best digraph results from 4.9% to 3.5%, trigraph results from 9.1% to 8.0% and keywords from 15.2% to 14.5%.

Further optimisation can be achieved by removing the worst 5 participants (15%) from the trial results. This provides an improvement in the results of the technique with average FAR's as low as 1.7% for digraphs, 4.4% for trigraphs and 12.8% for keywords (Table 7.12). While the keyword FAR in particular remains unacceptably high, a reference back to Table 7.10 reveals that there were still almost a third of users for whom 0% FAR was observed at the 0.5 standard deviation threshold. This suggests a clear potential for using the technique in a subset of cases – which could also increase if additional keyword typing samples were obtained to support the profiling.

| Metric   | S.D. | Unmatched Alert | FAR   |
|----------|------|-----------------|-------|
| Digraphs | 0.6  | No              | 1.7%  |
|          | 0.6  | Yes             | 2.4%  |
|          | 0.7  | No              | 2.2%  |
|          | 0.7  | Yes             | 7.0%  |
|          | 0.8  | No              | 4.9%  |
|          | 0.8  | Yes             | 17.0% |
| Trigrams | 0.5  | No              | 34.5% |
|          | 0.5  | Yes             | 4.4%  |
|          | 0.6  | No              | 29.3% |
|          | 0.6  | Yes             | 29.3% |
|          | 0.7  | No              | 25.6% |
|          | 0.7  | Yes             | 10.6% |
|          | 0.8  | No              | 21.2% |
|          | 0.8  | Yes             | 15.2% |
| Words    | 0.5  | No              | 13.8% |
|          | 0.6  | No              | 12.8% |
|          | 0.7  | No              | 15.3% |
|          | 0.8  | No              | 19.7% |

Table 7.12 - Optimised results

7.5 Conclusions

This chapter has presented the results of a series of trials aimed at implementing and evaluating keystroke analysis with a large number of trial participants over a longer period of time than the trials outlined in the previous chapter.

It is clear from the results presented here that there is considerable potential for continuous user authentication based upon keystroke analysis. The long-term sampling of keystroke digraphs has served to reinforce the validity of the technique, while the introduction of trigram and keyword-based monitoring has provided additional metrics that can be used as alternative (or complimentary) techniques. In particular, the use of keyword monitoring has considerable potential when used to monitor for specific, high-risk typed words (e.g. delete, format etc.).

# **Chapter 8**

## ***Extending Keystroke Analysis***

## 8.1 Introduction

The previous chapter presented a range of results derived from single-metric measures. While these measures provided good overall results, there was potential for improvement. This chapter considers the use of a composite approach to keystroke analysis, combining the three previously evaluated metrics – digraphs, trigraphs and keywords. It should be noted that the results presented in this chapter represent a subset of the overall results. Due to the number of variations in thresholds and standard deviation settings for each metric it was not possible to evaluate every possible setting and threshold. As such, this chapter presents initial *optimum* settings that provide *reasonable* results (the future work in the next chapter will suggest further refinements to this approach).

In addition to the composite approach, this chapter also describes a brief trial conducted using neural networks in an attempt to improve the performance of the digraph-based keystroke analysis considered in the previous chapter. Finally, the discussion presents details of a prototype real-time keystroke analysis system developed to demonstrate the concept of continuous, non-intrusive user authentication.

## 8.2 A composite approach

In order to evaluate a composite approach to keystroke analysis, the three separate keylogger data files described in the previous chapter were recombined (using Access queries) to create a single composite keylogger table. This resulted in a 700MB Access database containing 35 user keylogger tables.



Once the composite keylogger database was complete, a composite profile comparator was developed. This application was again developed in Visual Basic and was based on the data comparator presented in the previous chapter. The composite comparator (Figure 8.1) had a number of additional options and settings to determine the manner in which the composite data was compared to the reference profile.

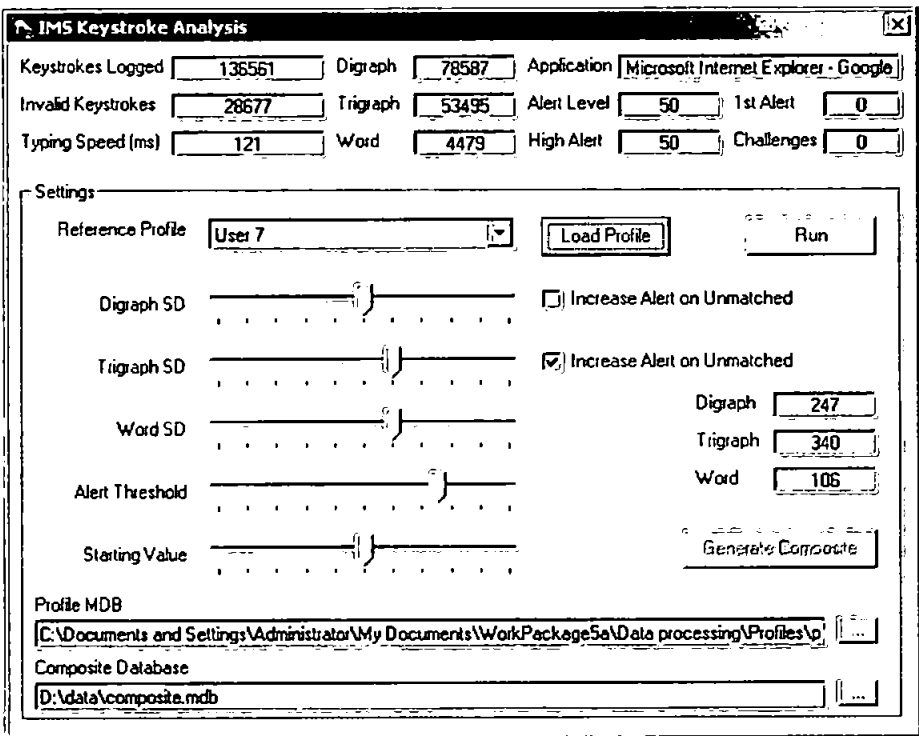


Figure 8.1 - Composite data comparator (running)

In the original comparator, each metric (digraph, trigraph and keyword) was evaluated separately, with a standard deviation setting adjustable for each profile. For the composite approach, all three settings were adjustable simultaneously together with an alert threshold and a variable starting value for the alert level (i.e. the initial confidence threshold was variable). In addition, the unmatched alert level increase was selectable for both digraphs and trigraphs. Once the profile had been selected from the drop down list and the

appropriate settings selected, the comparator was started. The comparator performed the same basic operation as the single-metric version described in the previous chapter. The users' profile was loaded and the digraph, trigraph and keyword profiles stored in memory for comparison. The alert level was initialised to a pre-determined value and then the composite data was loaded and processed one sample at a time. Each sample (either digraph, trigraph or keyword) was compared against the user profile and the alert level adjusted dependent on the match/unmatched status and the deviation from the mean with a set tolerance (according to the standard deviation setting).

$$\text{sample mean} \pm (\text{sample standard deviation} * \text{permitted deviation})$$

In the previous experiments the main consideration was to evaluate the alert level and to determine the FAR rate while fixing the FRR rate at 0%. The aim of this constraint was to ensure minimum inconvenience to the legitimate user (i.e. the monitoring software was optimised to never challenge the valid user). In this trial, a level of user inconvenience was considered acceptable – on the assumption that the user would pass any explicit challenge issued by the system (the nature of these challenges could be based upon basic passwords, or the authentication methods considered in chapter 4). While a number of user profiles offered 0% FAR in the previous trial, the difference between an impostor and the genuine user was frequently small (e.g. in one case the genuine user reached a highest alert level of 50 compared with the nearest impostor who reached 66). By fixing the FRR at 0%, it is possible that the nearest matching impostor (even when detected) were not significantly different to that of the genuine user.

|         | Digraph SD | Trigraph SD | Word SD | Unmatched Alert |          |
|---------|------------|-------------|---------|-----------------|----------|
|         |            |             |         | Digraph         | Trigraph |
| User 1  | 0.6        | 0.5         | 0.7     | No              | No       |
| User 2  | 0.6        | 0.5         | 0.5     | No              | No       |
| User 3  | 0.6        | 0.5         | 0.5     | No              | No       |
| User 4  | 0.7        | 0.6         | 0.6     | No              | No       |
| User 5  | 0.6        | 0.5         | 0.6     | No              | No       |
| User 6  | 0.7        | 0.6         | 0.6     | No              | No       |
| User 7  | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 8  | 0.7        | 0.6         | 0.5     | No              | Yes      |
| User 9  | 0.7        | 0.6         | 0.6     | No              | No       |
| User 10 | 0.7        | 0.6         | 0.6     | No              | No       |
| User 11 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 12 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 13 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 14 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 15 | 0.7        | 0.6         | 0.6     | No              | No       |
| User 16 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 17 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 19 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 20 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 21 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 22 | 0.7        | 0.6         | 0.6     | No              | No       |
| User 24 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 25 | 0.7        | 0.6         | 0.6     | No              | No       |
| User 26 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 27 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 28 | 0.7        | 0.6         | 0.6     | No              | No       |
| User 29 | 0.6        | 0.5         | 0.6     | No              | No       |
| User 31 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 32 | 0.7        | 0.6         | 0.6     | No              | Yes      |
| User 34 | 0.6        | 0.5         | 0.6     | No              | No       |

Table 8.1 - Composite profile settings

In order to address this issue (and to potentially improve the FAR rates in the previous chapter), this trial concentrated upon the number of keystrokes accepted for each user before a challenge was issued. This effectively fixed the alert level for all users at 70, the starting confidence/alert level at 50 and then varied the standard deviation and unmatched alert increase settings for each user profile comparison. The application settings were varied for each profile comparison in order to achieve the best distinction between the

genuine user and the impostors. The initial settings for each user were based upon the best performing settings from the earlier single-metric trials, and were then adjusted to obtain the best results (i.e. the optimisation was considered complete when the genuine user was able to type significantly more than an impostor before a challenge would have been issued by the system). The settings used for each user are shown in Table 8.1.

The results presented in Table 8.2 aimed to only challenge the genuine user after a significant number of samples had been processed (i.e. a genuine user would be infrequently challenged compared with the impostors). These results also show that an average of 4,759 digraphs were accepted before an impostor was challenged compared with an average of 76,228 digraphs before the valid user was challenged. While allowing an impostor to type large amounts of text is a considerable security risk, the average figure (4,759 samples) is significantly affected by a small number of users. When looking at Table 8.2, it is clear that the majority of impostors are detected in less than 200 samples (comprising digraphs, trigraphs and keywords). For most users, 200 samples equates to approximately 2 minutes of typing and as such is sufficient time to detect and challenge an impostor who is not intent on conducting serious damage. It is however possible that 200 samples would be more than enough to allow an impostor to issue sufficient commands to cause serious damage. For example, an impostor typing a high risk command like “format” would only generate 5 digraphs, 4 trigraphs and one keyword sample – insufficient to cause a challenge using the techniques described in this section. As such, it would be necessary to monitor for specific strings requiring a more definitive authentication prior to allowing the execution of the command.

| Reference Profiles |        |        |        |        |        |        |        |        |        |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |        |        |        |        |        |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|--------|--------|--------|--------|
|                    | User 1 | User 2 | User 3 | User 4 | User 5 | User 6 | User 7 | User 8 | User 9 | User 10 | User 11 | User 12 | User 13 | User 14 | User 15 | User 16 | User 17 | User 18 | User 19 | User 20 | User 21 | User 22 | User 23 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 30 | User 31 | User 32 | User 33 | User 34 |        |        |        |        |        |
| 34352              | 51     | 49     | 53     | 73     | 44     | 50     | 16     | 82     | 38     | 17      | 94      | 36      | 80      | 573     | 34      | 115     | 31      | 26      | 17      | 804     | 54      | 27      | 28      | 74      | 170     | 101     | 44      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23     |        |        |        |        |
| 50                 | 33065  | 27     | 46     | 50     | 161    | 63     | 83     | 34     | 489    | 202     | 79      | 153     | 87      | 53306   | 390     | 93      | 64      | 94      | 83      | 112     | 40      | 130     | 62      | 351     | 37      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23     | 23     | 23     |        |        |
| 849                | 96     | 156718 | 90     | 220    | 49     | 52     | 39     | 818    | 53     | 29      | 207     | 29      | 173     | 619     | 76      | 127     | 39      | 39      | 20      | 210     | 70      | 62      | 39      | 80      | 1706    | 76      | 43      | 32      | 76      | 76      | 76      | 76      | 76      | 76      | 76     | 76     | 76     |        |        |
| 72                 | 60     | 16     | 27324  | 23     | 34     | 37     | 16     | 47     | 28     | 11      | 181     | 22      | 71      | 167     | 47      | 27      | 14      | 17      | 26      | 22      | 25      | 42      | 72      | 63      | 21      | 16      | 16      | 16      | 16      | 16      | 16      | 16      | 16      | 16      | 16     | 16     |        |        |        |
| 181                | 29     | 117    | 23     | 50822  | 54     | 102    | 17     | 71     | 229    | 35      | 298     | 22      | 1780    | 367     | 29      | 224     | 35      | 35      | 34      | 60822   | 67      | 30      | 27      | 605     | 110     | 106     | 35      | 26      | 37      | 37      | 37      | 37      | 37      | 37      | 37     | 37     | 37     |        |        |
| 61                 | 37     | 20     | 31     | 61     | 320    | 34     | 20     | 21     | 42     | 103     | 176     | 37      | 41      | 67      | 35      | 323     | 42      | 50      | 32      | 17      | 23      | 43      | 42      | 910     | 17      | 23      | 13      | 16      | 48      | 48      | 48      | 48      | 48      | 48      | 48     | 48     |        |        |        |
| 744                | 57     | 102    | 52     | 17450  | 66     | 78579  | 66     | 78579  | 102    | 42      | 263     | 33      | 272     | 374     | 43      | 718     | 94      | 94      | 37      | 78579   | 83      | 43      | 46      | 71579   | 272     | 223     | 295     | 297     | 32      | 32      | 32      | 32      | 32      | 32      | 32     | 32     |        |        |        |
| 45                 | 30     | 25     | 24     | 63     | 61     | 68     | 71     | 29     | 47     | 30      | 44      | 47      | 45      | 280     | 40      | 50      | 34      | 47      | 29      | 29      | 29      | 56      | 54      | 40      | 47      | 13      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31     | 31     |        |        |        |
| 44                 | 21     | 31     | 35     | 39     | 39     | 41     | 12     | 37658  | 34     | 32      | 40      | 16      | 69      | 77      | 29      | 41      | 33      | 19      | 21      | 44      | 102     | 21      | 29      | 56      | 54      | 40      | 47      | 13      | 31      | 31      | 31      | 31      | 31      | 31      | 31     | 31     |        |        |        |
| 48                 | 69     | 12     | 63     | 32     | 38     | 29     | 28     | 52     | 70337  | 39      | 79      | 27      | 86      | 194     | 23      | 16      | 14      | 81      | 18      | 34      | 22      | 101     | 34      | 345     | 16      | 16      | 11      | 12      | 63      | 63      | 63      | 63      | 63      | 63      | 63     | 63     | 63     |        |        |
| 79                 | 234    | 19     | 36     | 67     | 64     | 51     | 70     | 38     | 522    | 187     | 59      | 64      | 447     | 345     | 59      | 72      | 49      | 64      | 54      | 720     | 53      | 38      | 42      | 94      | 34      | 40      | 49      | 35      | 317     | 317     | 317     | 317     | 317     | 317     | 317    | 317    | 317    |        |        |
| 142                | 133    | 61     | 137    | 63     | 72     | 49     | 39     | 71     | 121    | 66      | 20216   | 44      | 122     | 618     | 132     | 50      | 37      | 41      | 37      | 72      | 39      | 218     | 71      | 119     | 87      | 38      | 29      | 27      | 133     | 133     | 133     | 133     | 133     | 133     | 133    | 133    | 133    |        |        |
| 114                | 87     | 16     | 61     | 82     | 96     | 41     | 18     | 52     | 82     | 92      | 28      | 138     | 1043    | 32      | 216     | 27      | 87      | 18      | 22      | 22      | 27      | 25      | 124     | 46      | 49      | 16      | 24      | 12      | 19      | 18      | 18      | 18      | 18      | 18      | 18     | 18     | 18     |        |        |
| 137                | 27     | 64     | 48     | 156    | 53     | 87     | 25     | 100    | 46     | 381     | 91      | 44      | 31629   | 115     | 85      | 39      | 49      | 48      | 48      | 578     | 48      | 77      | 39      | 39      | 444     | 60      | 171     | 41      | 35      | 96      | 96      | 96      | 96      | 96      | 96     | 96     | 96     |        |        |
| 137                | 21     | 97     | 23     | 142    | 93     | 104    | 53     | 65     | 15351  | 29      | 30      | 78      | 473     | 15351   | 36      | 36      | 87      | 69      | 69      | 15351   | 56      | 21      | 27      | 489     | 63      | 142     | 53      | 54      | 80      | 80      | 80      | 80      | 80      | 80      | 80     | 80     |        |        |        |
| 66                 | 42839  | 37     | 69     | 100    | 83     | 50     | 41     | 44     | 42839  | 994     | 100     | 79      | 666     | 42839   | 42839   | 63      | 29      | 39      | 82      | 1053    | 49      | 104     | 64      | 983     | 59      | 58      | 26      | 28      | 42839   | 42839   | 42839   | 42839   | 42839   | 42839   | 42839  | 42839  | 42839  |        |        |
| 255                | 44     | 47     | 63     | 61     | 39     | 65     | 17     | 1539   | 23     | 23      | 63      | 33      | 105     | 175     | 44      | 105443  | 17      | 29      | 37      | 58      | 68      | 48      | 41      | 58      | 232     | 49      | 44      | 17      | 61      | 61      | 61      | 61      | 61      | 61      | 61     | 61     |        |        |        |
| 311                | 54     | 94     | 62     | 87     | 72     | 69     | 43     | 124    | 63     | 43      | 82      | 66      | 533     | 330     | 102     | 220     | 1273    | 43      | 48      | 103816  | 97      | 44      | 38      | 533     | 103     | 350     | 96      | 113     | 120     | 120     | 120     | 120     | 120     | 120     | 120    | 120    | 120    |        |        |
| 71                 | 69     | 53     | 63     | 57     | 46     | 53     | 29     | 57     | 78537  | 7658    | 113     | 25      | 78537   | 703     | 51      | 28      | 41      | 76537   | 257     | 78537   | 28      | 30      | 41      | 76537   | 52      | 78      | 21      | 38      | 126     | 126     | 126     | 126     | 126     | 126     | 126    | 126    | 126    |        |        |
| 111                | 80526  | 12     | 86     | 27     | 88     | 44     | 14     | 47     | 148    | 114     | 93      | 19      | 290     | 708     | 320     | 5       | 35      | 309     | 80626   | 115     | 32      | 47      | 61      | 114     | 30      | 74      | 18      | 12      | 167     | 167     | 167     | 167     | 167     | 167     | 167    | 167    | 167    |        |        |
| 359                | 69     | 180    | 78     | 175    | 65     | 71     | 25     | 266    | 106    | 153     | 193     | 65      | 262     | 715     | 87      | 147     | 53      | 57      | 28      | 117365  | 552     | 56      | 53      | 528     | 201     | 349     | 34      | 65      | 72      | 72      | 72      | 72      | 72      | 72      | 72     | 72     |        |        |        |
| 218                | 39     | 23     | 293    | 293    | 293    | 293    | 293    | 293    | 293    | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293    | 293    | 293    |        |        |
| User 23            | 87     | 129    | 16     | 232    | 41     | 47     | 44     | 21     | 31     | 241     | 47      | 273     | 27      | 65      | 79      | 80      | 31      | 23      | 36      | 44      | 40      | 27      | 38944   | 21      | 30      | 93      | 27      | 284     | 192     | 149     | 22      | 22      | 22      | 22      | 22     | 22     | 22     |        |        |
| User 24            | 218    | 39     | 23     | 293    | 293    | 293    | 293    | 293    | 293    | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293     | 293    | 293    | 293    |        |        |
| User 25            | 73     | 48463  | 11     | 211    | 44     | 144    | 31     | 14     | 63     | 53      | 53      | 48463   | 142     | 171     | 173     | 424     | 26      | 22      | 44      | 149     | 37      | 21      | 48463   | 48463   | 71      | 22      | 14      | 14      | 48463   | 48463   | 48463   | 48463   | 48463   | 48463   | 48463  | 48463  | 48463  |        |        |
| User 26            | 65     | 137    | 17     | 44     | 66     | 82     | 78     | 68     | 107    | 32      | 26      | 263     | 93      | 606     | 586     | 266     | 40      | 60      | 47      | 44      | 33068   | 27      | 98      | 83      | 33068   | 39      | 60      | 10      | 18      | 269     | 269     | 269     | 269     | 269     | 269    | 269    | 269    |        |        |
| User 27            | 505    | 30     | 354    | 79     | 69     | 96     | 49     | 49     | 93     | 93      | 34      | 21      | 81      | 27      | 305     | 54      | 630     | 25      | 32      | 23      | 70217   | 148     | 37      | 41      | 157     | 70217   | 179     | 53      | 76      | 29      | 29      | 29      | 29      | 29      | 29     | 29     | 29     |        |        |
| User 28            | 474    | 34     | 30     | 62     | 72     | 52     | 62     | 42     | 73     | 78      | 62      | 38      | 66      | 20      | 146     | 44      | 309     | 43      | 23      | 19      | 86653   | 74      | 49      | 35      | 61      | 309     | 86653   | 31      | 25      | 36      | 36      | 36      | 36      | 36      | 36     | 36     | 36     |        |        |
| User 29            | 318223 | 37     | 318223 | 38     | 38     | 54     | 153    | 26     | 318223 | 14      | 17      | 59      | 22      | 38      | 318223  | 38      | 318223  | 38      | 27      | 27      | 318223  | 318223  | 37      | 37      | 73      | 318223  | 318223  | 318223  | 318223  | 318223  | 318223  | 318223  | 318223  | 318223  | 318223 | 318223 | 318223 | 318223 | 318223 |
| User 30            | 1373   | 63     | 111    | 78     | 131    | 63     | 73     | 37     | 66     | 43      | 21      | 141     | 37      | 114     | 101     | 70      | 61      | 53      | 31      | 21      | 128     | 371     | 64      | 37      | 603     | 3113    | 89      | 30      | 353867  | 38      | 38      | 38      | 38      | 38      | 38     | 38     | 38     | 38     |        |
| User 31            | 48     | 73     | 22     | 123    | 21     | 77     | 34     | 18     | 38     | 84      | 83      | 396     | 45      | 73      | 2430    | 73      | 209     | 22      | 30      | 34      | 82      | 34      | 101     | 42      | 85      | 26      | 48      | 20      | 24      | 124409  | 24      | 24      | 24      | 24      | 24     | 24     | 24     | 24     |        |

Table 8.2 - Number of keypresses before a challenge (composite)

When considering the inconvenience to genuine users the results indicate that a user would only be challenged after approximately 5 hours of work – with some users only being challenged after 50 days of typing. Given that most users will authenticate at least once a day, an authentication challenge after the equivalent of 50 days of typing is unlikely to ever occur in normal operation.

### **8.3 Neural Network Approach**

Following the analysis conducted in the previous chapter, a brief final trial was conducted using a neural network approach. There has been relatively little research conducted using neural networks to authenticate keystrokes with the two published works listed in chapter 5 (Brown & Rogers, 1993 and Furnell et al., 1996) both considering the use of neural networks on static keystroke data. The work presented in this section considers the use of neural network techniques on dynamic keystroke data (i.e. continuous monitoring).

Due to the volume of data and the complexity of the required networks, it was necessary to create a reduced subset of data upon which to base the neural network analysis. The first stage was to extract a number of common samples across all user profiles. For the purposes of this experiment, the top ten commonly occurring digraphs (across all profiles) were selected. It should be noted that while lists are available for common digraph pairs in the English language; these did not match the data logged by these experiments with the top ten digraphs showing variation across all users. Table 8.3 presents the minimum and maximum occurrence counts for each digraph pair across all user profiles (this reflects the range of sample sizes originally presented in the previous chapter).

| Digraph | Min | Max  |
|---------|-----|------|
| TH      | 319 | 8845 |
| IN      | 214 | 8643 |
| HE      | 212 | 7901 |
| TE      | 352 | 7503 |
| ES      | 135 | 6298 |
| ON      | 271 | 5824 |
| AN      | 135 | 5239 |
| AT      | 193 | 5164 |
| SE      | 167 | 4553 |
| ST      | 92  | 3530 |

Table 8.3 - Profile counts of common digraphs

As it was necessary to have a common sample size for each input chosen for the neural network, the minimum sample count for each digraph pair determined the profile sample size (i.e. each user’s data needed to share a common subset of digraphs with a common number of samples per digraph). In order to optimise the accuracy of the network; a number of user profiles were removed in order to increase the fixed sample size for the neural network (a higher number of samples is likely to increase the classification accuracy). Having removed the worst performing profiles (the five users identified in earlier experiments), the resultant digraph counts are shown in Table 8.4.

| Digraph | Min | Max  |
|---------|-----|------|
| TH      | 407 | 8845 |
| IN      | 512 | 8643 |
| HE      | 426 | 7901 |
| TE      | 333 | 7503 |
| ES      | 356 | 6298 |
| ON      | 328 | 5824 |
| AN      | 446 | 5239 |
| AT      | 206 | 5164 |
| SE      | 258 | 4553 |
| ST      | 227 | 3530 |

Table 8.4 - Reduced profile counts of common digraphs

The reduced profile counts shown in Table 8.4 provide a maximum data set size of 200 samples per digraph. This effectively provided 2000 samples per user (200 samples x 10 digraphs). This data was randomly extracted from the original keylogger files (i.e. for each

digraph, 200 random samples were selected from the raw keylogger file and then saved as text files in preparation for the neural network analysis).

The neural network was configured as a ten input, multi-layer perceptron network with each of the ten inputs representing one of the digraphs (Figure 8.2). The data was then fed into the neural network for each user, with the resultant overall FAR/FRR chart shown in Figure 8.3.

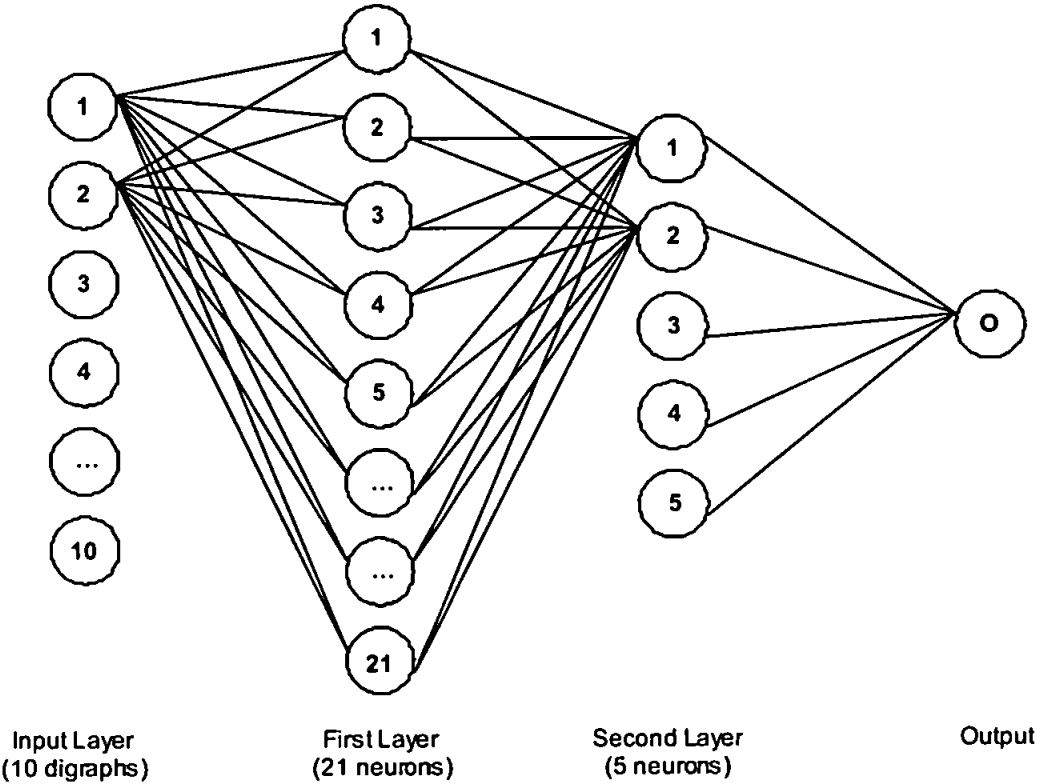


Figure 8.2 - Neural network configuration (21:5:1)



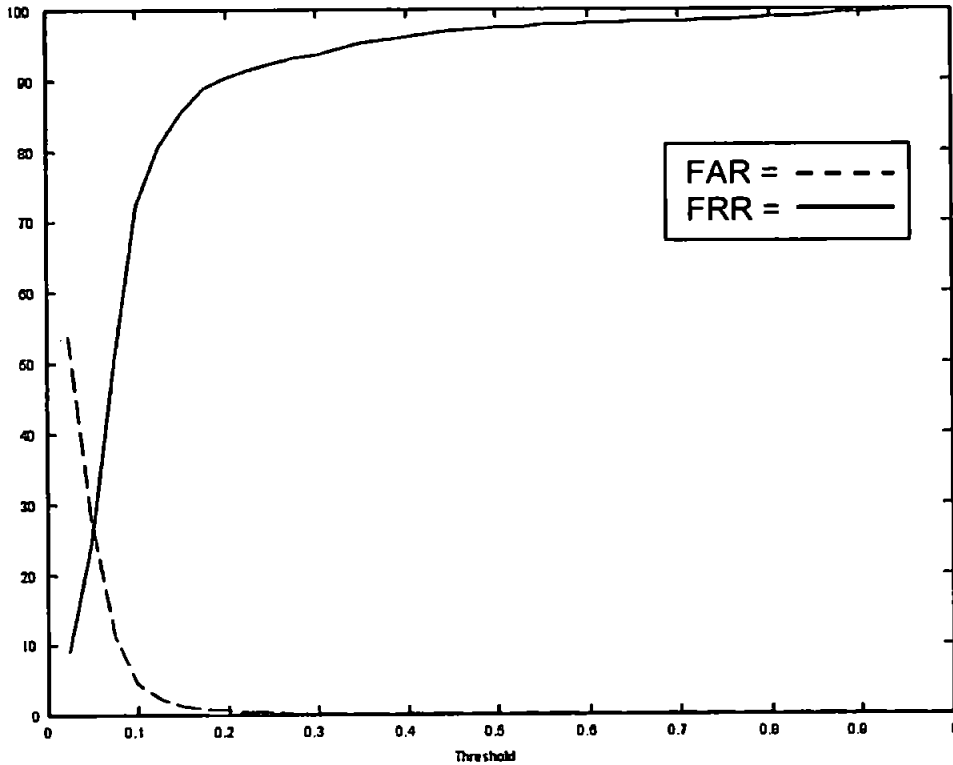


Figure 8.3 - Overall FAR/FRR rates for all users

Figure 8.3 shows the relationship between the average FAR and FRR with an Equal Error Rate (EER) of approximately 24.9%. It should be noted that the neural network approach utilised only a small proportion of the overall data set and as such is only an indication of the potential performance that this technique may offer. For several users, the common ten digraphs were not representative of the ten highest occurring digraphs for their profile – it is likely that by increasing the number of inputs to the network a higher degree of authentication could be achieved (i.e. increasing the number of digraphs on which users are classified).

The results from the neural network approach are presented here as an indication of the applicability of the approach to the problem of keystroke analysis, and it is hoped that further work would improve the classification of users and hence reduce the EER by optimising the training and size of the neural network.

## 8.4 A prototype demonstrator for comprehensive user authentication

In addition to the comparator illustrated in Figure 8.1 (that processed keystroke data effectively off-line), a real-time keystroke analysis demonstrator was developed. This program implements the keylogging and profile comparison features into a single application. The screen-shot shown in Figure 8.4 illustrates the dynamic alert level as a continuous moving line in white, with alerts/challenges shown in red. In addition, the digraph alert level is shown in green with corresponding lines for trigraphs (yellow) and keywords (blue). In this example, a challenge would have been issued at the mid-point of the plot where the alert level reached 75 (the threshold for a challenge was set at 70 and is indicated in the figure by a broken cyan line). The screen-shot also indicates the number of challenges in the current session together with the number of keystrokes before the first challenge was issued. It should be noted that the example chart in Figure 8.4 shows no further activity in the latter part of the plot – i.e. the horizontal lines indicate no keyboard activity. It can also be observed that there is no deviation in the keyword (blue line) alert level as this profile had relatively few profiled keywords.

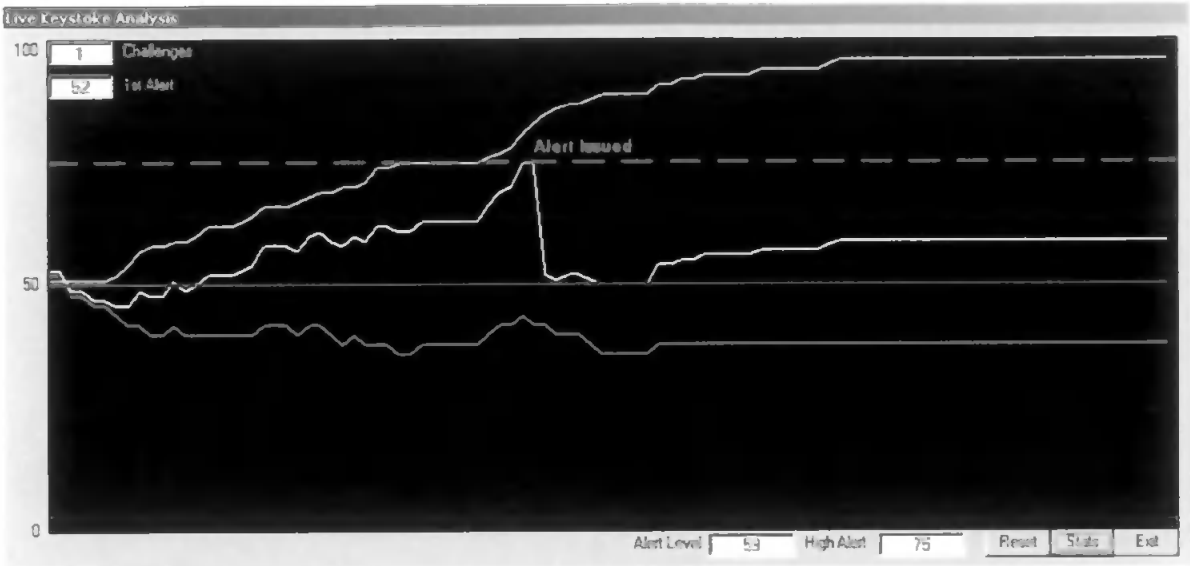


Figure 8.4 - Live keystroke analysis demonstrator – impostor (detected)

Figure 8.5 and Figure 8.6 illustrate two further typing sessions. Both figures are based upon a genuine user typing with different profile settings. Figure 8.5 was based on the default settings (i.e. not optimised for the individual user) and shows considerable difference between the digraphs (shown in green – high acceptance) and the trigraphs (shown in yellow – low acceptance) thus resulting in a moderate composite acceptance rate (shown in white). When considering Figure 8.6, the same user has a much better (and more consistent) overall acceptance rate and hence a lower alert level for digraphs and trigraphs.

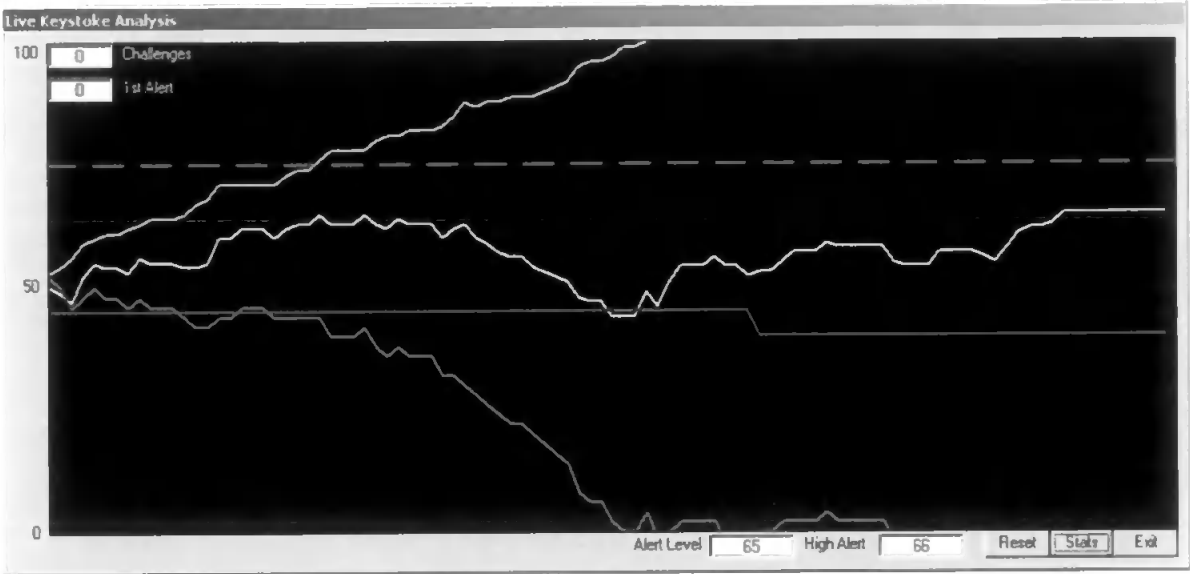


Figure 8.5 - Live keystroke analysis demonstrator – genuine user (default settings)

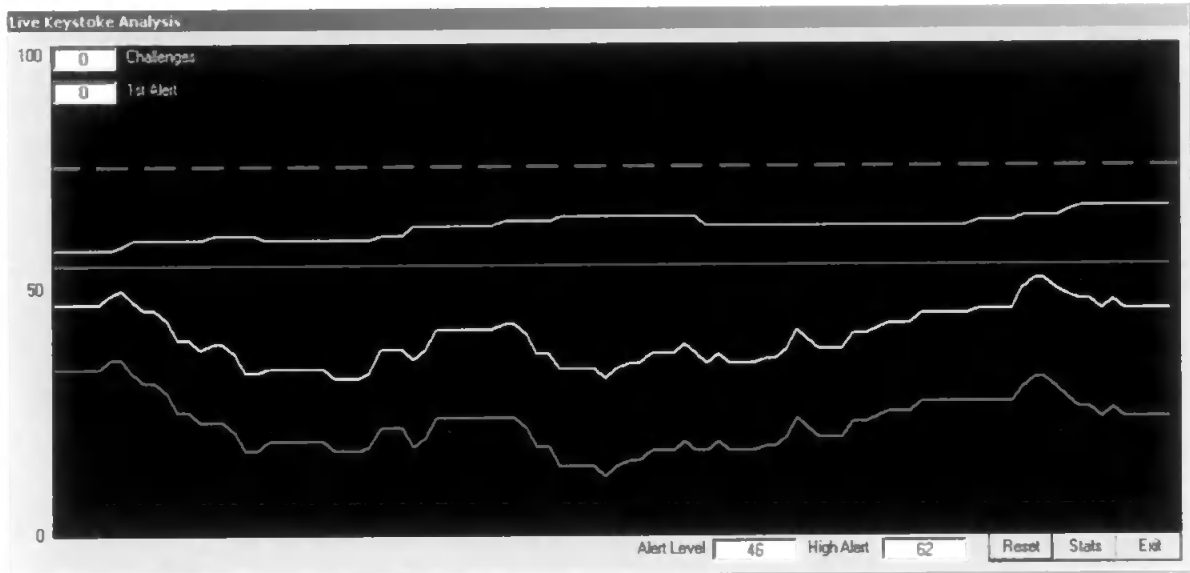


Figure 8.6 - Live keystroke analysis demonstrator – genuine user (optimised settings)

The live keystroke analysis application also has a similar options window to that of the off-line comparator shown in Figure 8.1, which allows a range of options to be selected to determine the comparisons made against the reference profile (illustrated in Figure 8.7).

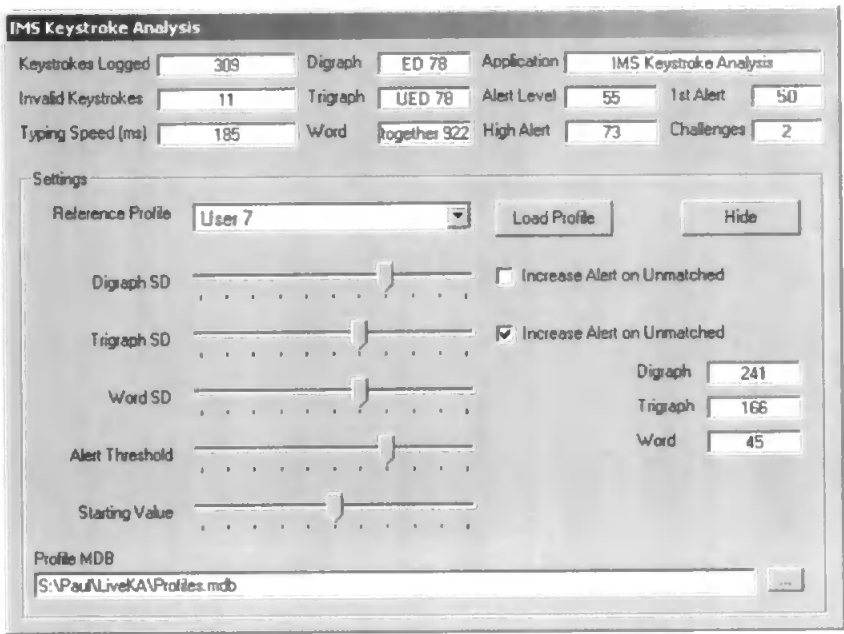


Figure 8.7 - Live keystroke analysis options

8.5 Conclusions

This chapter has further extended the novel approach to keystroke analysis. The combination of all three metrics into a single composite metric has shown significant potential, with genuine users able to work unhindered for hours (up to days) while impostors (with few exceptions) were only able to type for two minutes prior to an authentication challenge being triggered.

In addition to the results for the composite techniques, this chapter has also presented an overview of a demonstrator system capable of composite keystroke analysis coupled with a selection of challenge techniques to respond to alerts raised by the system.

While the results show keystroke analysis is a viable authentication technique, it is also clear that the analytical approach does not provide sufficient distinction for all users and a live implementation would have to consider which metric (if any) is most appropriate for each user. Over time, the profiles would also need to be updated to reflect variations in typing style and the possibility of improvement (or degradation) in a user's typing abilities. It is envisaged that keystroke analysis would become only one of a number of monitoring techniques used by a more comprehensive system together with other authentication and supervision techniques. Such a system would be able to select appropriate authentication and supervision techniques for the current user working with the resources available on the computer.

# **Chapter 9**

## ***Conclusions***

## 9.1 Achievements of the research programme

The research programme has met all of the objectives outlined in the first chapter. The main achievements of this research programme were.

- Identifying user attitudes and opinions to login and continuous user authentication. This justified the selection and development of the alternative authentication techniques.
- Implementation and evaluation of novel continuous user authentication approaches based upon digraphs, trigraphs and keywords. The use of trigraph and keyword authentication represents novel work in the authentication domain.
- Design of novel methods for implementing and evaluating composite continuous user authentication. The use of composite user authentication represents entirely new work in this domain.
- Development of a proof-of-concept prototype composite authentication and response system. This demonstrated the concept of continuous non-intrusive user authentication using keystroke analysis.

The thesis began by describing current authentication techniques and proposing alternatives before evaluating user attitudes and opinions to the current authentication methods as well as their opinions on a range of alternative authentication and continuous

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supervision techniques. Having identified a preference for secret-based approaches, the thesis presented the results of a series of trials conducted to evaluate the use of password, ImagePIN and cognitive/associative questions. These approaches demonstrated that while users still prefer secret-based methods, their frequent inability to use them both reliably and properly (in accordance with guidelines on correct use) indicated that alternative techniques are needed. While other methods were available, a key requirement concerning the selection of an alternative approach was that an ideal technique must be transparent to the user (i.e. it must have little/no impact on the users' normal activity). In order to achieve this objective, non-intrusive authentication mechanisms were considered. Having eliminated a number of alternatives (due to their intrusive nature or the cost of dedicated hardware), keystroke analysis was selected for a number of experimental trials.

To evaluate keystroke analysis, a series of experiments aimed at implementing and evaluating alternative user authentication techniques were conducted and are described in detail in chapters 6, 7 and 8. These experiments evaluated keystroke analysis in an unconstrained manner monitoring keystroke activity across all applications in a users' session. Users were authenticated on digraph, trigraph and keyword metrics with further trials conducted to evaluate the performance of composite metrics.

In addition to the simple analysis approach used, a number of alternatives have been considered. In chapters 6 and 7, the use of data mining and neural network approaches were evaluated and while both of these techniques were able to provide a level of user classification, there was insufficient time to fully investigate their applicability and as such they will be discussed in section 9.3 as part of the future work proposals. In addition to

these two techniques, section 9.3 also outlined the potential for the application-specific keystroke analysis method described in chapter 6.

Several papers relating to the research programme have been presented at refereed conferences and in appropriate international journals (a complete list is presented in Appendix D together with a subset of relevant papers). As such, it is believed that the research has made valid and useful contributions to the information system security field.

## 9.2 Limitations of the research

Although the research programme met the objectives outlined in chapter 1, there were a number of limitations to the research.

1. The survey conducted in chapter 2 assessed a limited range of participants and as such is not representative of the wider population. User attitudes towards alternative forms of user authentication have, as a consequence, been assessed by dominantly IT-literate individuals (mainly drawn from academic staff and students). Had the survey been conducted across a wider cross-section of the public, it is probable that acceptance for continuous user authentication would have been ranked less favourably due to the *big-brother* concerns of the general public. However, this does not unduly affect the consequent selection of non-intrusive continuous monitoring techniques since the most likely use for these methods is within an organisational context.

2. The alternative techniques described in chapter 4 were assessed using a limited number of users – all of whom were drawn from staff and students within the University. To give a more rounded viewpoint, it would have been ideal to have had a wider population participating in the trial. However, there were technical limitations that required a supervised installation and guidance for the users before participating.
3. The experiments conducted in chapters 6 and 7 were both limited in terms of the duration of the trial and the number of participants. The first experiment was limited to one month's duration with 10 participants to provide an initial set of results to inform the implementation of more comprehensive follow-on tests. The later experiment's duration was constrained to three months with 34 participants in order to meet deadlines for the entire research programme. Obtaining more participants was a significant problem in both experiments due to reluctance on the part of some users to be monitored and the lack of cooperation from management when approached for permission to install the software for members of administrative staff. Despite these limitations, the experiments were able to proceed, albeit with fewer participants than hoped for.
4. There were also limitations in the analysis techniques used – in particular, the data mining and neural network approaches could have been expanded further, as described in the next section.

## **9.3 Future work**

Throughout the research programme, a number of extensions to the project have been considered. While some of these ideas have been discussed in the body of the thesis, this section presents a range of potential ideas for future work to progress the research beyond the PhD programme.

### **9.3.1 Data mining approach**

In chapter 6, the use of data mining was considered as an alternative approach. This technique did not prove to be a reliable method – only achieving a classification accuracy of 50%. Using larger data sets and a reduced set of digraphs (in the same manner as the neural network approach discussed in chapter 8), it may be possible to improve the classification accuracy quoted. However, the benefits of this approach may not be sufficient to warrant the time needed to analyse and classify user samples. It may, however, be of use when enrolling users and developing the initial authentication profile, as the data mining approach may detect more subtle distinguishing characteristics than the current methods.

### **9.3.2 Neural network approach**

The results presented in chapter 8 showed an overall Equal Error Rate (EER) of 26% for the neural network approach. While this error rate is far too high for a usable system, it does indicate a correlation between the genuine user and their profile; and a system able to distinguish between genuine users and impostors. Further research may be able to improve

the acceptance rates through optimisation of the training methods used coupled with changes in the neural network construction and size.

### **9.3.3 Optimised composite metric comparison parameters**

In chapter 8, the use of composite keystroke analysis was evaluated using a range of settings in the data comparator (e.g. varying the deviation thresholds etc.). While the results from these trials were considered acceptable, further refinement could improve the FAR/FRR rates to detect impostors quickly while avoiding any unnecessary interruption to the genuine user. Due to the range of settings that could be applied (e.g. 0.5-0.8 standard deviations for the metrics, the inclusion of unmatched alert increases and the alert threshold) there are at least six variables that can be adjusted independently of each other resulting in several hundred potential combinations per profile.

In order to improve the error rates encountered in chapter 8, it would be necessary to optimise the settings used for each profile. This would require an iterative approach to home-in on a suitable group of settings.

### **9.3.4 Application-specific profiles**

Chapter 6 proposed the use of application specific profiles in order to differentiate between a users' typing behaviour in individual application contexts. The results from this section demonstrated differences in typing styles between classes of applications, but further work is required to (a) determine if these differences remain once sufficient data is available to produce a profile, and (b) determine if certain users can be authenticated more accurately

using application specific profiles or by using the application-independent approaches already demonstrated.

The data gathered in chapter 7 has not, at this stage, been processed for application profiles, as such; this will be one of the first elements of the post-thesis research. It is likely that, given the increased size of keylogger files, there will be an improvement over the results presented in chapter 6.

### **9.3.5 Application-specific monitoring**

Following the previous section, it may be advantageous to have specific monitoring enabled for individual applications. For example, when a user is interacting with a command interpreter (e.g. the DOS shell), they are unlikely to be typing sufficient keystrokes to authenticate the user. However, the misuse-potential for such applications is high (e.g. the user could reformat the hard disk or delete key files). As such, it may be beneficial to monitor specific applications more rigorously than others in order to detect an impostor in a shorter period of time (e.g. using keyword-based monitoring).

### **9.3.6 Keyword Latencies**

The keystroke analysis presented in this thesis has considered the latencies of digraphs, trigraphs and keywords. However, there may also be scope for monitoring of the individual digraph (or trigraph) elements of the monitored keywords. For example, when monitoring the keyword 'format', rather than just monitoring the overall latency, the digraphs FO, OR, RM, MA and AT could be evaluated (equally the trigraphs FOR, ORM,

RMA and MAT could be used). As such, keyword profiles would require a series of timings, rather than the single timing value currently used.

### **9.3.7 Larger-Scale Trial**

Having demonstrated the reliability of continuous supervision using keystroke analysis, it would be necessary to implement a larger trial using a greater number of trial participants over a longer period of time. It would also be necessary to ensure the participants represent a less homogenous range of users (i.e. ensuring a wider range of typing abilities and IT literacy are represented by the trial user group).

### **9.3.8 Statistical Analysis**

In addition to extending the trial to include a wider range of participants, further work should be conducted to investigate the use of formal statistical analysis on the data generated using the techniques described in this thesis.

### **9.3.9 Response System**

In addition to the user monitoring proposed in this thesis, it is also necessary to respond to the challenges issued by the monitoring system. The ImagePin and cognitive question methods from chapter 4 are potential candidates for this role, as they would allow a valid user to quickly authenticate and continue to work while preventing an impostor from proceeding. The issue of response is currently being investigated in another research programme (Papadaki et al., 2002)

### **9.3.10 Implementation issues**

To implement the proposed monitoring system, it would also be necessary to consider the wider framework in which the system would be placed. It is envisaged that a monitoring system would be activated upon satisfactory authentication by the operating system. Following this, the monitoring system would automatically monitor user activity and respond with a challenge in the event that the alert level increased beyond a pre-defined threshold. To realise a system of this nature under Windows would require considerable low-level access to the operating system in order to guarantee that a user could be denied access to their computer in the event of suspicious activity. Investigating the wider implementation of a comprehensive monitoring system forms a part of a number of Intrusion Monitoring System (IMS) related projects building on the original work of Furnell (1995).

## **9.4 Conclusions**

The role of information technology in both the work and home environments has increased beyond any imaginable boundary. As part of the increasing pervasiveness of IT, we have to accept that our computer systems will be increasingly vulnerable to attack and misuse. The simple fact that computer users are unable to apply even the simplest form of protection (the humble password) in a secure and appropriate manner demonstrates that alternative forms of securing IT systems are required.

This research has emphasised the role of security in modern computer systems and has focussed upon addressing the need for reliable and dependable user authentication and



supervision. The application of a single authentication mechanism or monitoring technique is in itself insufficient to guarantee system security. Instead a comprehensive security system is required to initially authenticate and subsequently monitor and challenge users as appropriate. Such a system would have to adapt to the differences between users, and apply appropriate authentication and supervision techniques for each one, as well as having the ability to learn from the user over time and to adapt to discrete changes in natural behaviour. In addition to the ability to authenticate and monitor, the ideal system would also have to respond to perceived impostor activity with an appropriate challenge in order to more confidently authenticate the user. All of this needs to occur as transparently as possible in order to achieve the requirement of non-intrusiveness so often required by users.

In conclusion, the research presented in this thesis has addressed a number of authentication issues. A mechanism has been developed to monitor a users' session in a non-intrusive manner by evaluating normal typing patterns. This has demonstrated that a user can be authenticated in a transparent manner without requiring any explicit action. However, the reliability with which this can be done is dependent on a number of factors and, as such, cannot be used as the sole method of authentication. Instead, the techniques described in this thesis can evaluate user characteristics that could be monitored as part of a much wider authentication and supervision framework.

Authentication will remain a crucial factor in protecting access to the applications and services we depend upon in our day-to-day lives. With greater access to information and the introduction of new services like e-Voting, e-Health etc., the need for effective and reliable authentication techniques will only increase.

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# **Appendix A**

## ***Survey Form and Results***

## **Additional Survey Material**

This appendix contains additional material to support chapter 3. The first part of this appendix includes a printed copy of the questionnaire form that was distributed to potential respondents, while the second part presents the collated results from the relevant sections of the survey. In addition to the raw results, a number of summary tables are presented, together with additional charts not included in the body of the thesis.



# **Computer Crime And Abuse Survey**

## **A Survey of Attitudes and Awareness**

**Paul Dowland**

I am currently undertaking a Ph.D. in the field of network security. This survey aims to establish people's awareness of computer crime and abuse and their attitudes towards it. In addition, attitudes towards new security techniques will be assessed.

The first section of the survey asks about your general details, including use of computers at home and at work. The second section looks at the area of computer crime and abuse, your awareness of it and your opinions on how it is treated by the media. The final section assesses your opinions about the acceptability of various security techniques and their benefits to different business sectors.

Most of the questions require tick-box responses although a few require a short written answer.

Please feel free to add any additional comments wherever you feel it is necessary.

The survey is anonymous and the information will be treated confidentially.

The survey will take approximately 20 minutes to complete.  
Please ensure you have enough time to complete the survey.

An on-line version of this survey can be found at

<http://jack.sec.plym.ac.uk/survey>

Please feel free to distribute this URL.

**Thank you for you co-operation.**

---

### **Contact address**

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## Section One - General Details

1. Sex  
Male ☐ Female ☐
2. Age Group  
16 -24 ☐ 25 -34 ☐ 35 -49 ☐ 50 -64 ☐ 65+ ☐
3. Which of the following categories best describes your current (or intended) occupation?
- |                                                                          |                                                        |
|--------------------------------------------------------------------------|--------------------------------------------------------|
| <input type="checkbox"/> Government                                      | <input type="checkbox"/> Manufacturing                 |
| <input type="checkbox"/> Defence                                         | <input type="checkbox"/> Engineering                   |
| <input type="checkbox"/> Education                                       | <input type="checkbox"/> Travel Industries and Tourism |
| <input type="checkbox"/> Health                                          | <input type="checkbox"/> Property Services             |
| <input type="checkbox"/> Social and Public Services                      | <input type="checkbox"/> Communications Industry       |
| <input type="checkbox"/> Banking, Finance and Insurance                  | <input type="checkbox"/> Computing Industry            |
| <input type="checkbox"/> Utility Services (Water, Gas, Electricity etc.) |                                                        |
- Other, please specify \_\_\_\_\_

4. Educational qualifications  
None ☐ GCSEs ☐ O-levels ☐ A-levels ☐ Degree ☐  
Other, please specify \_\_\_\_\_
5. Do you read a newspaper on a regular basis? If yes, is it a broadsheet or tabloid newspaper?  
Broadsheet ☐ Tabloid ☐
6. Have you ever used a computer?  
Yes ☐ No ☐ *If no, please go to Section 2.*
7. For how many years have you used a computer?
- |                                           |                                        |                                       |
|-------------------------------------------|----------------------------------------|---------------------------------------|
| Less than 1 year <input type="checkbox"/> | 1 - 5 years <input type="checkbox"/>   | 6 - 10 years <input type="checkbox"/> |
| 11 - 15 years <input type="checkbox"/>    | 16 - 20 years <input type="checkbox"/> | 20+ years <input type="checkbox"/>    |

### Use of computer at work

8. Do you use a computer at work?  
Yes ☐ No ☐ *If no, please go to Question 15.*
9. Approximately how many hours per day do you use it?
- |                                           |                                            |
|-------------------------------------------|--------------------------------------------|
| Less than 1 hour <input type="checkbox"/> | 1 - 4 hours <input type="checkbox"/>       |
| 4 - 8 hours <input type="checkbox"/>      | More than 8 hours <input type="checkbox"/> |
10. Do you have access to Internet e-mail and the World Wide Web at work?  
Yes ☐ No ☐
11. What applications do you use it for? Please indicate how often you use each application.
- |                         | Often                    | Occasionally             | Never                    |
|-------------------------|--------------------------|--------------------------|--------------------------|
| Word-processing         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Spreadsheet             | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Database                | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Desktop Publishing      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Software Development    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Graphical Design        | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Engineering/Scientific  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Web-browsing            | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| E-mail                  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Games                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Computer Aided Learning | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

- |                                                                                               | Yes                      | No                       | Don't know               |
|-----------------------------------------------------------------------------------------------|--------------------------|--------------------------|--------------------------|
| 12. Have you ever used unlicensed software at work?                                           | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 13. Have you ever used the office computer for activities that are not related to your work ? | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 14. Have you ever used someone else's password or account without their consent or knowledge? | <input type="checkbox"/> | <input type="checkbox"/> |                          |

**Use of computer at home**

15. Do you have a computer at home?

Yes ☐ No ☐

*If no, please go to Section 2.*

16. Approximately how many hours per week do you use it?

Never ☐ 1 - 5 hours ☐  
6 - 15 hours ☐ 15+ hours ☐

17. Do you have access to the Internet at home?

Yes ☐ No ☐

18. What applications do you use your home computer for? Please indicate how often you use each application.

|                         | Often                    | Occasionally             | Never                    |
|-------------------------|--------------------------|--------------------------|--------------------------|
| Word-processing         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Spreadsheet             | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Database                | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Desktop Publishing      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Software Development    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Graphical Design        | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Engineering/Scientific  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Web-browsing            | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| E-mail                  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Games                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Computer Aided Learning | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

19. Have you ever used unlicensed software at home?

Yes ☐ No ☐

## Section Two - Computer Crime and Abuse

Computer systems and networks are increasingly becoming a part of everyday life. Many institutions, including banks and hospitals, use them to hold personal records. Many businesses would no longer be able to operate without them. As their use increases so the move towards a new society, an information society, comes a step closer. It is argued that this information society will be, and is, subject to many of the problems that exist in society. This section of the survey is dedicated to the problem of computer crime and abuse and people's awareness of the problem, as well as the part that the media plays in portraying such news.

20. Please rate the following acts of computer crime and abuse. Rate on a scale from very serious to no crime at all.

|                               | Very Serious             |                          | Indifferent              |                          | No Crime                 |
|-------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Viruses.                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Viewing someone else's data.  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Altering someone else's data. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Theft of computer equipment.  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Copying software.             | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Copying data.                 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Computer fraud.               | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Sabotage.                     | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

21. Do you consider computer crime and abuse to be:-

|                      | Agree                    | Disagree                 | Neutral                  |
|----------------------|--------------------------|--------------------------|--------------------------|
| Not a problem?       | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| A technical problem? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| An ethical problem?  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

22. Are you aware of the following UK legislation:-

|                      | Yes                      | No                       |
|----------------------|--------------------------|--------------------------|
| Data Protection Act? | <input type="checkbox"/> | <input type="checkbox"/> |
| Computer Misuse Act? | <input type="checkbox"/> | <input type="checkbox"/> |

23. Please describe in a few words your image of a hacker.

---



---

24. Do you consider 'hacking' to be:-

|                         | Yes                      | No                       | Don't know               |
|-------------------------|--------------------------|--------------------------|--------------------------|
| Acceptable?             | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| An invasion of privacy? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Theft?                  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

25. Do you think that people hack:-

|                                | Yes                      | No                       | Don't know               |
|--------------------------------|--------------------------|--------------------------|--------------------------|
| Out of curiosity?              | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| To make money?                 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| For the thrill of it?          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| To "beat the system"?          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| For malicious reasons?         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Please give any other reasons. | <hr/>                    |                          |                          |

|                                                                                                                                          | Yes                      | No                       | Don't know               |
|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------|--------------------------|
| 26. Regarding confessed or convicted hackers:-                                                                                           |                          |                          |                          |
| Should they be allowed to work in the computing field?                                                                                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Should they be allowed to have a computer at home?                                                                                       | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 27. Do you think that acting via a computer makes hackers feel less responsible for their actions?                                       | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 28. Do you think that a user would act differently if their activity was being monitored and recorded?                                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 29. Is it acceptable to read information on someone else's computer, without their permission, as long as you do not alter or damage it? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 30. Have you read about or heard of any computer crime cases in the news?                                                                | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 31. Are you aware of any of the following:-                                                                                              |                          |                          |                          |
|                                                                                                                                          | Yes                      | No                       |                          |
| 'Chaos Computer Club'?                                                                                                                   | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 'Kevin Mitnick'?                                                                                                                         | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 'Michelangelo' virus?                                                                                                                    | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 'Zebedee virus'?                                                                                                                         | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 'Friday the 13 <sup>th</sup> ' virus?                                                                                                    | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 'War Games'?                                                                                                                             | <input type="checkbox"/> | <input type="checkbox"/> |                          |
| 32. Other than the above, do you remember any other computer crime and abuse cases or keywords that you have read or heard about?        | <hr/> <hr/>              |                          |                          |
| 33. In your opinion, how does the media treat the issue of computer crime and abuse?                                                     | <hr/> <hr/>              |                          |                          |
| 34. In your opinion, how do films treat the issue of computer crime and abuse?                                                           | <hr/> <hr/>              |                          |                          |

### Section Three - User Authentication and Supervision

As computers become more widely used, so the need for stronger security techniques becomes more important. Current research and evolving technologies are making new security techniques available. These techniques ensure that users are who they claim to be - this is known as *authentication* of identity. Some can also continuously monitor the authenticity of the user and the legitimacy of their activity - this is known as *supervision*. Some of these techniques are able to verify a user's identity using their physical characteristics whilst others analyse their behaviour. Physical characteristics that can be recognised include a user's face, eye (iris scanning), hand and fingerprint. Behavioural characteristics include a user's typing style (keystroke analysis), their use of the mouse (mouse dynamics), the way they sign their name (signature analysis) or their voice characteristics (voice verification).

35. Are any of the following security monitoring methods currently used in your workplace?

|                                        | Yes                      | No                       | Unsure                   |
|----------------------------------------|--------------------------|--------------------------|--------------------------|
| Password                               | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Restricted number of password attempts | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Audit trails                           | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Virus scanners                         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Access restrictions                    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Other, please specify \_\_\_\_\_

If passwords are used, please answer questions 36 - 43 inclusive.

36. How many different systems or applications do you use that require a password? Please indicate how many.

\_\_\_\_\_

37. Do you use a different password for each one?

Yes ☐ No ☐

38. How often do you change your password?

- ☐ Weekly  
☐ Fortnightly  
☐ Monthly  
☐ Six-monthly  
☐ Less frequently  
☐ Never

|                                                                                                                    | Yes                      | No                       | Unsure                   |
|--------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------|--------------------------|
| 39. Are you forced to change your password after a certain length of time?                                         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 40. Is a minimum password length enforced?                                                                         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 41. Do you write your password(s) down?                                                                            | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 42. Does anyone else know your password(s)?                                                                        | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 43. Do you think that your password could be easily guessed e.g. is it part of your address, name, partner's name? | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

If virus scanners are used, please answer questions 44 and 45.

44. Is the virus scanner run at login?  
Yes ☐ No ☐ Unsure ☐

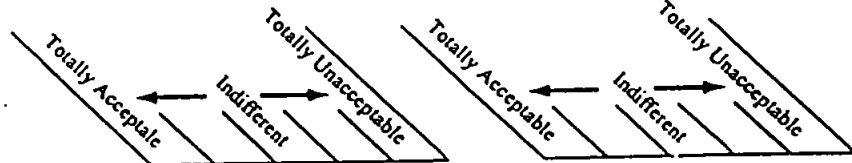
45. How often is the virus scanner run?  
Daily ☐ Weekly ☐ Monthly ☐ Less frequently ☐ Unsure ☐

### Security techniques

46. How acceptable to you would the following techniques be when used for:-  
a) initial login authentication (where user identification is verified when they begin using the system)?  
b) continuous monitoring (where user identification is verified periodically whilst the user is logged in)?

initial login authentication

continuous monitoring



#### Password

The most common method in current systems.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Keystroke analysis

Research has shown that users have different typing styles and that they can be identified by measuring the times between keystrokes.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Face recognition

A snapshot of the user, taken by a camera positioned on the monitor, is compared with a previously stored 'faceprint'.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Mouse dynamics

Similar to keystroke analysis, users can be identified by the way in which they use the mouse.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Voice verification

A user's voice, when speaking a word or phrase into the computer's microphone, is compared with a previously stored 'voiceprint'.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Signature analysis

A user signs their name using a special pen and pad, the signature is digitised and compared with a previously stored version.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Iris scanning

A snapshot of the user's iris, taken by a camera, is compared with a previously stored image.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Hand geometry

This technique measures the physical dimensions of the hand using a small camera and compares these with previously stored values.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#### Fingerprint analysis

An automated version of the fingerprint identification system similar to that traditionally used in criminology.

☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

47. Do you consider continuous monitoring, in general, to be acceptable? Yes      No      Unsure  
☐ ☐ ☐

48. Most of these techniques require a user-profile to be set up. This is a stored record of the user's characteristics which gives the computer system a reference for comparisons.

How long would you be prepared to spend in order to set up your user-profile?

- No time ☐  
 Up to 5 minutes ☐  
 Up to 15 minutes ☐  
 Up to 30 minutes ☐  
 Up to 1 hour ☐  
 More than 1 hour ☐

49. Such approaches are not 100% accurate - how frequently would you be prepared for the system to reject you and then demand that you login once again?

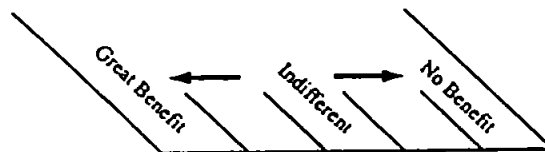
- Hourly ☐  
 Daily ☐  
 Weekly ☐  
 Never ☐

50. Would you regard supervision of your activities by the computer as an invasion of your personal privacy? Yes      No      Unsure  
☐ ☐ ☐

51. Would you trust your organisation to only use the monitoring for security purposes? Yes      No      Unsure  
☐ ☐ ☐

52. Should users be aware that they are being monitored? Yes      No      Unsure  
☐ ☐ ☐

53. Which fields/sectors do you consider would benefit from supervision of users by the computer? Please rate from a great benefit to no benefit at all.



|                                                 |                          |                          |                          |                          |                          |
|-------------------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Government                                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Defence                                         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Education                                       | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Health                                          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Social and Public Services                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Banking, Finance and Insurance                  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Utility Services (Water, Gas, Electricity etc.) | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Manufacturing                                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Engineering                                     | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Travel Industries and Tourism                   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Property Services                               | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Communications Industry                         | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| Computing Industry                              | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Please check that you have answered all the questions.

Thank you for your cooperation.



## Collated survey results

### Survey Method

Online

Paper

| Count of Method |       |
|-----------------|-------|
| Method          | Total |
| Online          | 27    |
| Paper           | 148   |
| (blank)         |       |
| Grand Total     | 175   |

### Q1 Sex

Male

Female

| Count of Q1 |       |
|-------------|-------|
| Q1          | Total |
| 0           | 140   |
| 1           | 35    |
| (blank)     |       |
| Grand Total | 175   |

### Q2 Age group

16-24

25-34

35-49

50-64

| Count of Q2 |       |
|-------------|-------|
|             | Total |
| 0           | 73    |
| 1           | 56    |
| 2           | 34    |
| 3           | 12    |
| (blank)     |       |
| Grand Total | 175   |

### Q3 Occupation

Banking, Finance & Insurance

Computing Industry

Communications Industry

Defence

Education

Engineering

Government

Health

Manufacturing

Social and Public Services

Travel Industries and Tourism

Utility Services (Water, Gas, Electricity etc.)

Other

| Count of Q3 |       |
|-------------|-------|
| Q3          | Total |
| 0           | 1     |
| 1           | 25    |
| 2           | 37    |
| 3           | 3     |
| 4           | 27    |
| 5           | 41    |
| 6           | 3     |
| 7           | 6     |
| 8           | 1     |
| 10          | 4     |
| 11          | 5     |
| 12          | 4     |
| 13          | 18    |
| (blank)     |       |
| Grand Total | 175   |

**Q4 Qualifications**

None  
GCSE  
O-Level  
A-Level  
Degree  
Other

| Count of Q4 |   |       |
|-------------|---|-------|
| Q4          |   | Total |
|             | 0 | 6     |
|             | 1 | 10    |
|             | 2 | 16    |
|             | 3 | 46    |
|             | 4 | 77    |
|             | 5 | 20    |
| (blank)     |   |       |
| Grand Total |   | 175   |

**Q5 Newspapers**

Broadsheet  
Tabloid  
None

| Count of Q5 |   |       |
|-------------|---|-------|
| Q5          |   | Total |
|             | 0 | 65    |
|             | 1 | 48    |
|             | 2 | 62    |
| (blank)     |   |       |
| Grand Total |   | 175   |

**Q6 Used a computer**

Yes  
No

| Count of Q6 |   |       |
|-------------|---|-------|
| Q6          |   | Total |
|             | 0 | 170   |
|             | 1 | 5     |
| (blank)     |   |       |
| Grand Total |   | 175   |

**Q7 Years of computer use**

<1 year  
1-5 years  
6-10 years  
11-15 years  
16-20 years  
20+years

| Count of Q7 |   |       |
|-------------|---|-------|
| Q7          |   | Total |
|             | 0 | 3     |
|             | 1 | 33    |
|             | 2 | 53    |
|             | 3 | 43    |
|             | 4 | 31    |
|             | 5 | 7     |
| (blank)     |   |       |
| Grand Total |   | 170   |

**Q8 Use computer at work**

Yes  
No

| Count of Q8 |   |       |
|-------------|---|-------|
| Q8          |   | Total |
|             | 0 | 151   |
|             | 1 | 20    |
| (blank)     |   |       |
| Grand Total |   | 171   |

**Q9 Hours of use**

<1 hour  
1-4 hours  
4-8 hours  
>8 hours

| Count of Q9 |   |       |
|-------------|---|-------|
| Q9          |   | Total |
|             | 0 | 10    |
|             | 1 | 65    |
|             | 2 | 63    |
|             | 3 | 14    |
| (blank)     |   |       |
| Grand Total |   | 152   |

**Q10 WWW/Email access**

Yes

No

| Count of Q10 |       |
|--------------|-------|
| Q10          | Total |
| 0            | 129   |
| 1            | 18    |
| (blank)      |       |
| Grand Total  | 147   |

**Q11a Word Processing**

Often

Occasionally

Never

| Count of Q11a |       |
|---------------|-------|
| Q11a          | Total |
| 0             | 115   |
| 1             | 28    |
| 2             | 6     |
| (blank)       |       |
| Grand Total   | 149   |

**Q11b Spreadsheet**

Often

Occasionally

Never

| Count of Q11b |       |
|---------------|-------|
| Q11b          | Total |
| 0             | 50    |
| 1             | 67    |
| 2             | 25    |
| (blank)       |       |
| Grand Total   | 142   |

**Q11c Database**

Often

Occasionally

Never

| Count of Q11c |       |
|---------------|-------|
| Q11c          | Total |
| 0             | 29    |
| 1             | 72    |
| 2             | 37    |
| (blank)       |       |
| Grand Total   | 138   |

**Q11d Desktop Publishing**

Often

Occasionally

Never

| Count of Q11d |       |
|---------------|-------|
| Q11d          | Total |
| 0             | 17    |
| 1             | 49    |
| 2             | 71    |
| (blank)       |       |
| Grand Total   | 137   |

**Q11e Software Development**

Often

Occasionally

Never

| Count of Q11e |       |
|---------------|-------|
| Q11e          | Total |
| 0             | 57    |
| 1             | 37    |
| 2             | 44    |
| (blank)       |       |
| Grand Total   | 138   |

**Q11f Graphical Design**

Often  
Occasionally  
Never

| Count of Q11f |   |       |
|---------------|---|-------|
| Q11f          |   | Total |
|               | 0 | 18    |
|               | 1 | 49    |
|               | 2 | 67    |
| (blank)       |   |       |
| Grand Total   |   | 134   |

**Q11g Engineering/Scientific**

Often  
Occasionally  
Never

| Count of Q11g |   |       |
|---------------|---|-------|
| Q11g          |   | Total |
|               | 0 | 44    |
|               | 1 | 47    |
|               | 2 | 45    |
| (blank)       |   |       |
| Grand Total   |   | 136   |

**Q11h Web-browsing**

Often  
Occasionally  
Never

| Count of Q11h |   |       |
|---------------|---|-------|
| Q11h          |   | Total |
|               | 0 | 88    |
|               | 1 | 39    |
|               | 2 | 18    |
| (blank)       |   |       |
| Grand Total   |   | 145   |

**Q11i E-Mail**

Often  
Occasionally  
Never

| Count of Q11i |   |       |
|---------------|---|-------|
| Q11i          |   | Total |
|               | 0 | 113   |
|               | 1 | 20    |
|               | 2 | 14    |
| (blank)       |   |       |
| Grand Total   |   | 147   |

**Q11j Games**

Often  
Occasionally  
Never

| Count of Q11j |   |       |
|---------------|---|-------|
| Q11j          |   | Total |
|               | 0 | 21    |
|               | 1 | 64    |
|               | 2 | 58    |
| (blank)       |   |       |
| Grand Total   |   | 143   |

**Q11k Computer aided learning**

Often  
Occasionally  
Never

| Count of Q11k |   |       |
|---------------|---|-------|
| Q11k          |   | Total |
|               | 0 | 5     |
|               | 1 | 63    |
|               | 2 | 68    |
| (blank)       |   |       |
| Grand Total   |   | 136   |

**Q12 Use of unlicensed software**

Yes  
No  
Don't Know

| Count of Q12 |       |
|--------------|-------|
| Q12          | Total |
| 0            | 53    |
| 1            | 66    |
| 2            | 35    |
| (blank)      |       |
| Grand Total  | 154   |

**Q13 Use of office computer for non-work activities**

Yes  
No

| Count of Q13 |       |
|--------------|-------|
| Q13          | Total |
| 0            | 116   |
| 1            | 38    |
| (blank)      |       |
| Grand Total  | 154   |

**Q14 Use of other's password/account**

Yes  
No

| Count of Q14 |       |
|--------------|-------|
| Q14          | Total |
| 0            | 31    |
| 1            | 122   |
| (blank)      |       |
| Grand Total  | 153   |

**Q15 Computer at home**

Yes  
No

| Count of Q15 |       |
|--------------|-------|
| Q15          | Total |
| 0            | 144   |
| 1            | 27    |
| (blank)      |       |
| Grand Total  | 171   |

**Q16 Hours of use**

Never  
1 to 4  
6 to 15  
15 +

| Count of Q16 |       |
|--------------|-------|
| Q16          | Total |
| 0            | 3     |
| 1            | 60    |
| 2            | 47    |
| 3            | 33    |
| (blank)      |       |
| Grand Total  | 143   |

**Q17 WWW/Email access**

Yes  
No

| Count of Q17 |       |
|--------------|-------|
| Q17          | Total |
| 0            | 69    |
| 1            | 74    |
| (blank)      |       |
| Grand Total  | 143   |

**Q18a Word Processing**

Often  
Occasionally  
Never

| Count of Q18a |       |
|---------------|-------|
| Q18a          | Total |
| 0             | 112   |
| 1             | 27    |
| 2             | 2     |
| (blank)       |       |
| Grand Total   | 141   |

**Q18b Spreadsheet**

Often  
Occasionally  
Never

| Count of Q18b |       |
|---------------|-------|
| Q18b          | Total |
| 0             | 42    |
| 1             | 67    |
| 2             | 25    |
| (blank)       |       |
| Grand Total   | 134   |

**Q18c Database**

Often  
Occasionally  
Never

| Count of Q18c |       |
|---------------|-------|
| Q18c          | Total |
| 0             | 17    |
| 1             | 56    |
| 2             | 52    |
| (blank)       |       |
| Grand Total   | 125   |

**Q18d Desktop Publishing**

Often  
Occasionally  
Never

| Count of Q18d |       |
|---------------|-------|
| Q18d          | Total |
| 0             | 22    |
| 1             | 47    |
| 2             | 57    |
| (blank)       |       |
| Grand Total   | 126   |

**Q18e Software Development**

Often  
Occasionally  
Never

| Count of Q18e |       |
|---------------|-------|
| Q18e          | Total |
| 0             | 37    |
| 1             | 52    |
| 2             | 39    |
| (blank)       |       |
| Grand Total   | 128   |

**Q18f Graphical Design**

Often  
Occasionally  
Never

| Count of Q18f |       |
|---------------|-------|
| Q18f          | Total |
| 0             | 26    |
| 1             | 46    |
| 2             | 57    |
| (blank)       |       |
| Grand Total   | 129   |

**Q18g Engineering/Scientific**

Often  
Occasionally  
Never

| Count of Q18g |       |
|---------------|-------|
| Q18g          | Total |
| 0             | 35    |
| 1             | 48    |
| 2             | 45    |
| (blank)       |       |
| Grand Total   | 128   |

**Q18h Web-browsing**

Often  
Occasionally  
Never

| Count of Q18h |       |
|---------------|-------|
| Q18h          | Total |
| 0             | 49    |
| 1             | 20    |
| 2             | 60    |
| (blank)       |       |
| Grand Total   | 129   |

**Q18i E-Mail**

Often  
Occasionally  
Never

| Count of Q18i |       |
|---------------|-------|
| Q18i          | Total |
| 0             | 51    |
| 1             | 21    |
| 2             | 58    |
| (blank)       |       |
| Grand Total   | 130   |

**Q18j Games**

Often  
Occasionally  
Never

| Count of Q18j |       |
|---------------|-------|
| Q18j          | Total |
| 0             | 56    |
| 1             | 54    |
| 2             | 27    |
| (blank)       |       |
| Grand Total   | 137   |

**Q18k Computer aided learning**

Often  
Occasionally  
Never

| Count of Q18k |       |
|---------------|-------|
| Q18k          | Total |
| 0             | 6     |
| 1             | 40    |
| 2             | 81    |
| (blank)       |       |
| Grand Total   | 127   |

**Q19 Use of unlicensed software**

Yes  
No

| Count of Q19 |       |
|--------------|-------|
| Q19          | Total |
| 0            | 106   |
| 1            | 37    |
| (blank)      |       |
| Grand Total  | 143   |

Questions 20 to 34 considered issues relating to computer crime and abuse. These results have not been included here as they are not relevant to the PhD research. The full results can be found on the CD at the rear of the thesis.

**Use of monitoring methods**

**Q35a Password**

Yes

No

Unsure

| Count of Q35a |   |       |
|---------------|---|-------|
| Q35a          |   | Total |
|               | 0 | 160   |
|               | 1 | 9     |
|               | 2 | 2     |
| (blank)       |   |       |
| Grand Total   |   | 171   |

**Q35b Restricted password attempts**

Yes

No

Unsure

| Count of Q35b |   |       |
|---------------|---|-------|
| Q35b          |   | Total |
|               | 0 | 91    |
|               | 1 | 44    |
|               | 2 | 32    |
| (blank)       |   |       |
| Grand Total   |   | 167   |

**Q35c Audit trails**

Yes

No

Unsure

| Count of Q35c |   |       |
|---------------|---|-------|
| Q35c          |   | Total |
|               | 0 | 47    |
|               | 1 | 49    |
|               | 2 | 66    |
| (blank)       |   |       |
| Grand Total   |   | 162   |

**Q35d Virus scanners**

Yes

No

Unsure

| Count of Q35d |   |       |
|---------------|---|-------|
| Q35d          |   | Total |
|               | 0 | 145   |
|               | 1 | 12    |
|               | 2 | 11    |
| (blank)       |   |       |
| Grand Total   |   | 168   |

**Q35e Access restrictions**

Yes

No

Unsure

| Count of Q35e |   |       |
|---------------|---|-------|
| Q35e          |   | Total |
|               | 0 | 139   |
|               | 1 | 13    |
|               | 2 | 13    |
| (blank)       |   |       |
| Grand Total   |   | 165   |



**Q36 Number of systems using passwords**

| Count of Q36 |     |       |
|--------------|-----|-------|
| Q36          |     | Total |
| 1            | 31  |       |
| 2            | 32  |       |
| 3            | 24  |       |
| 4            | 16  |       |
| 5            | 13  |       |
| 6            | 6   |       |
| 7            | 4   |       |
| 8            | 2   |       |
| 9            | 1   |       |
| 10           | 11  |       |
| 12           | 2   |       |
| 20           | 3   |       |
| 25           | 1   |       |
| 100          | 1   |       |
| 150          | 1   |       |
| (blank)      |     |       |
| Grand Total  | 148 |       |

**Q37 Different password for systems**

Yes

No

| Count of Q37 |     |       |
|--------------|-----|-------|
| Q37          |     | Total |
| 0            | 81  |       |
| 1            | 70  |       |
| (blank)      |     |       |
| Grand Total  | 151 |       |

**Q38 Frequency of password changes**

Weekly

Fortnightly

Monthly

Six-Monthly

Less Frequently

Never

| Count of Q38 |     |       |
|--------------|-----|-------|
| Q38          |     | Total |
| 0            | 3   |       |
| 1            | 2   |       |
| 2            | 40  |       |
| 3            | 28  |       |
| 4            | 32  |       |
| 5            | 53  |       |
| (blank)      |     |       |
| Grand Total  | 158 |       |

**Q39 Forced to change password**

Yes

No

Unsure

| Count of Q39 |     |       |
|--------------|-----|-------|
| Q39          |     | Total |
| 0            | 56  |       |
| 1            | 89  |       |
| 2            | 11  |       |
| (blank)      |     |       |
| Grand Total  | 156 |       |

**Q40 Minimum password length**

Yes  
No  
Unsure

| Count of Q40 |   |       |
|--------------|---|-------|
| Q40          |   | Total |
|              | 0 | 111   |
|              | 1 | 26    |
|              | 2 | 21    |
| (blank)      |   |       |
| Grand Total  |   | 158   |

**Q41 Write down passwords**

Yes  
No

| Count of Q41 |   |       |
|--------------|---|-------|
| Q41          |   | Total |
|              | 0 | 27    |
|              | 1 | 131   |
| (blank)      |   |       |
| Grand Total  |   | 158   |

**Q42 Anyone else know password**

Yes  
No  
Unsure

| Count of Q42 |   |       |
|--------------|---|-------|
| Q42          |   | Total |
|              | 0 | 51    |
|              | 1 | 94    |
|              | 2 | 13    |
| (blank)      |   |       |
| Grand Total  |   | 158   |

**Q43 Easily guessed password**

Yes  
No  
Unsure

| Count of Q43 |   |       |
|--------------|---|-------|
| Q43          |   | Total |
|              | 0 | 24    |
|              | 1 | 125   |
|              | 2 | 9     |
| (blank)      |   |       |
| Grand Total  |   | 158   |

**Q44 Virus scanner run at login**

Yes  
No  
Unsure

| Count of Q44 |   |       |
|--------------|---|-------|
| Q44          |   | Total |
|              | 0 | 106   |
|              | 1 | 31    |
|              | 2 | 17    |
| (blank)      |   |       |
| Grand Total  |   | 154   |

**Q45 How often is virus scanner run**

Daily  
Weekly  
Monthly  
Less Frequently  
Unsure

| Count of Q45 |   |       |
|--------------|---|-------|
| Q45          |   | Total |
|              | 0 | 97    |
|              | 1 | 16    |
|              | 2 | 6     |
|              | 3 | 7     |
|              | 4 | 28    |
| (blank)      |   |       |
| Grand Total  |   | 154   |

Question 46 considered the acceptability of a range of authentication techniques, the left pivot tables present the rating of the approach specified for initial login authentication while the right pivot tables present the rating for continuous monitoring.

**Q46a Password**

0=Totally Acceptable

1=Acceptable

2=Indifferent

3=Unacceptable

4=Totally Unacceptable

| Count of Q46aa |       |
|----------------|-------|
| Q46aa          | Total |
| 0              | 148   |
| 1              | 10    |
| 2              | 5     |
| 4              | 1     |
| (blank)        |       |
| Grand Total    | 164   |

| Count of Q46ab |       |
|----------------|-------|
| Q46ab          | Total |
| 0              | 40    |
| 1              | 13    |
| 2              | 35    |
| 3              | 30    |
| 4              | 39    |
| (blank)        |       |
| Grand Total    | 157   |

**Q46b Keystroke Analysis**

| Count of Q46ba |       |
|----------------|-------|
| Q46ba          | Total |
| 0              | 61    |
| 1              | 21    |
| 2              | 45    |
| 3              | 15    |
| 4              | 19    |
| (blank)        |       |
| Grand Total    | 161   |

| Count of Q46bb |       |
|----------------|-------|
| Q46bb          | Total |
| 0              | 43    |
| 1              | 35    |
| 2              | 41    |
| 3              | 10    |
| 4              | 28    |
| (blank)        |       |
| Grand Total    | 157   |

**Q46c Face Recognition**

| Count of Q46ca |       |
|----------------|-------|
| Q46ca          | Total |
| 0              | 76    |
| 1              | 30    |
| 2              | 28    |
| 3              | 15    |
| 4              | 12    |
| (blank)        |       |
| Grand Total    | 161   |

| Count of Q46cb |       |
|----------------|-------|
| Q46cb          | Total |
| 0              | 39    |
| 1              | 22    |
| 2              | 39    |
| 3              | 25    |
| 4              | 31    |
| (blank)        |       |
| Grand Total    | 156   |

**Q46d Mouse Dynamics**

| Count of Q46da |       |
|----------------|-------|
| Q46da          | Total |
| 0              | 59    |
| 1              | 16    |
| 2              | 44    |
| 3              | 16    |
| 4              | 25    |
| (blank)        |       |
| Grand Total    | 160   |

| Count of Q46db |       |
|----------------|-------|
| Q46db          | Total |
| 0              | 46    |
| 1              | 29    |
| 2              | 40    |
| 3              | 13    |
| 4              | 28    |
| (blank)        |       |
| Grand Total    | 156   |

**Q46e Voice Verification**

| Count of Q46ea |       |
|----------------|-------|
| Q46ea          | Total |
| 0              | 83    |
| 1              | 26    |
| 2              | 29    |
| 3              | 11    |
| 4              | 12    |
| (blank)        |       |
| Grand Total    | 161   |

| Count of Q46eb |       |
|----------------|-------|
| Q46eb          | Total |
| 0              | 32    |
| 1              | 27    |
| 2              | 36    |
| 3              | 25    |
| 4              | 35    |
| (blank)        |       |
| Grand Total    | 155   |

**Q46f Signature Analysis**

| Count of Q46fa |       |
|----------------|-------|
| Q46fa          | Total |
| 0              | 72    |
| 1              | 25    |
| 2              | 33    |
| 3              | 14    |
| 4              | 18    |
| (blank)        |       |
| Grand Total    | 162   |

| Count of Q46fb |       |
|----------------|-------|
| Q46fb          | Total |
| 0              | 24    |
| 1              | 10    |
| 2              | 32    |
| 3              | 33    |
| 4              | 57    |
| (blank)        |       |
| Grand Total    | 156   |

**Q46g Iris Scanning**

| Count of Q46ga |       |
|----------------|-------|
| Q46ga          | Total |
| 0              | 78    |
| 1              | 28    |
| 2              | 25    |
| 3              | 10    |
| 4              | 20    |
| (blank)        |       |
| Grand Total    | 161   |

| Count of Q46gb |       |
|----------------|-------|
| Q46gb          | Total |
| 0              | 34    |
| 1              | 16    |
| 2              | 29    |
| 3              | 33    |
| 4              | 43    |
| (blank)        |       |
| Grand Total    | 155   |

**Q46h Hand Geometry**

| Count of Q46ha |       |
|----------------|-------|
| Q46ha          | Total |
| 0              | 74    |
| 1              | 28    |
| 2              | 30    |
| 3              | 12    |
| 4              | 18    |
| (blank)        |       |
| Grand Total    | 162   |

| Count of Q46hb |       |
|----------------|-------|
| Q46hb          | Total |
| 0              | 29    |
| 1              | 18    |
| 2              | 31    |
| 3              | 39    |
| 4              | 39    |
| (blank)        |       |
| Grand Total    | 156   |

**Q46i Fingerprint Analysis**

| Count of Q46ia |       |
|----------------|-------|
| Q46ia          | Total |
| 0              | 85    |
| 1              | 24    |
| 2              | 23    |
| 3              | 10    |
| 4              | 20    |
| (blank)        |       |
| Grand Total    | 162   |

| Count of Q46ib |       |
|----------------|-------|
| Q46ib          | Total |
| 0              | 36    |
| 1              | 15    |
| 2              | 29    |
| 3              | 35    |
| 4              | 41    |
| (blank)        |       |
| Grand Total    | 156   |

**Q47 Monitoring acceptable**

Yes  
No  
Unsure

| Count of Q47 |       |
|--------------|-------|
| Q47          | Total |
| 0            | 75    |
| 1            | 49    |
| 2            | 40    |
| (blank)      |       |
| Grand Total  | 164   |

**Q48 User-profile set-up time**

No time  
Upto 5 mins  
Upto 15 mins  
Upto 30 mins  
Upto 1hr  
> 1hr

| Count of Q48 |       |
|--------------|-------|
| Q48          | Total |
| 0            | 18    |
| 1            | 59    |
| 2            | 39    |
| 3            | 22    |
| 4            | 19    |
| 5            | 8     |
| (blank)      |       |
| Grand Total  | 165   |

**Q49 Frequency of system rejection**

Hourly  
Daily  
Weekly  
Never

| Count of Q49 |       |
|--------------|-------|
| Q49          | Total |
| 0            | 12    |
| 1            | 45    |
| 2            | 60    |
| 3            | 48    |
| (blank)      |       |
| Grand Total  | 165   |

**Q50 Invasion of privacy**

Yes  
No  
Unsure

| Count of Q50 |       |
|--------------|-------|
| Q50          | Total |
| 0            | 70    |
| 1            | 73    |
| 2            | 25    |
| (blank)      |       |
| Grand Total  | 168   |

**Q51 Monitoring for security only**

Yes  
No  
Unsure

| Count of Q51 |       |
|--------------|-------|
| Q51          | Total |
| 0            | 50    |
| 1            | 79    |
| 2            | 39    |
| (blank)      |       |
| Grand Total  | 168   |

**Q52 Awareness of monitoring**

Yes  
No  
Unsure

| Count of Q52 |       |
|--------------|-------|
| Q52          | Total |
| 0            | 149   |
| 1            | 12    |
| 2            | 7     |
| (blank)      |       |
| Grand Total  | 168   |

The final question (53) presented a list of sectors and asked for comments on the benefit to each sector.

**Q53a Government**

Great benefit

Indifferent

No benefit

| Count of Q53a |       |
|---------------|-------|
| Q53a          | Total |
| 0             | 128   |
| 1             | 27    |
| 2             | 10    |
| 3             | 1     |
| 4             | 3     |
| (blank)       |       |
| Grand Total   | 169   |

**Q53b Defence**

Great benefit

Indifferent

No benefit

| Count of Q53b |       |
|---------------|-------|
| Q53b          | Total |
| 0             | 152   |
| 1             | 10    |
| 2             | 4     |
| 3             | 1     |
| 4             | 2     |
| (blank)       |       |
| Grand Total   | 169   |

**Q53c Education**

Great benefit

Indifferent

No benefit

| Count of Q53c |       |
|---------------|-------|
| Q53c          | Total |
| 0             | 40    |
| 1             | 42    |
| 2             | 62    |
| 3             | 11    |
| 4             | 13    |
| (blank)       |       |
| Grand Total   | 168   |

**Q53d Health**

Great benefit

Indifferent

No benefit

| Count of Q53d |       |
|---------------|-------|
| Q53d          | Total |
| 0             | 85    |
| 1             | 46    |
| 2             | 27    |
| 3             | 5     |
| 4             | 6     |
| (blank)       |       |
| Grand Total   | 169   |

**Q53e Social & Public Services**

Great benefit

Indifferent

No benefit

| Count of Q53e |       |
|---------------|-------|
| Q53e          | Total |
| 0             | 68    |
| 1             | 47    |
| 2             | 33    |
| 3             | 11    |
| 4             | 10    |
| (blank)       |       |
| Grand Total   | 169   |

**Q53f Banking, Finance & Insurance**

Great benefit

Indifferent

No benefit

| Count of Q53f |       |
|---------------|-------|
| Q53f          | Total |
| 0             | 129   |
| 1             | 27    |
| 2             | 9     |
| 4             | 3     |
| (blank)       |       |
| Grand Total   | 168   |

**Q53g Utility Services**

Great benefit

Indifferent

No benefit

| Count of Q53g |       |
|---------------|-------|
| Q53g          | Total |
| 0             | 45    |
| 1             | 38    |
| 2             | 63    |
| 3             | 11    |
| 4             | 11    |
| (blank)       |       |
| Grand Total   | 168   |

**Q53h Manufacturing**

Great benefit

Indifferent

No benefit

| Count of Q53h |       |
|---------------|-------|
| Q53h          | Total |
| 0             | 26    |
| 1             | 41    |
| 2             | 76    |
| 3             | 18    |
| 4             | 8     |
| (blank)       |       |
| Grand Total   | 169   |

**Q53i Engineering**

Great benefit

Indifferent

No benefit

| Count of Q53i |       |
|---------------|-------|
| Q53i          | Total |
| 0             | 34    |
| 1             | 43    |
| 2             | 63    |
| 3             | 19    |
| 4             | 10    |
| (blank)       |       |
| Grand Total   | 169   |

**Q53j Travel Industries and Tourism**

Great benefit

Indifferent

No benefit

| Count of Q53j |    |       |
|---------------|----|-------|
| Q53j          |    | Total |
| 0             | 17 |       |
| 1             | 31 |       |
| 2             | 80 |       |
| 3             | 25 |       |
| 4             | 16 |       |
| (blank)       |    |       |
| Grand Total   |    | 169   |

**Q53k Property Services**

Great benefit

Indifferent

No benefit

| Count of Q53k |    |       |
|---------------|----|-------|
| Q53k          |    | Total |
| 0             | 27 |       |
| 1             | 33 |       |
| 2             | 79 |       |
| 3             | 15 |       |
| 4             | 15 |       |
| (blank)       |    |       |
| Grand Total   |    | 169   |

**Q53l Communications Industry**

Great benefit

Indifferent

No benefit

| Count of Q53l |    |       |
|---------------|----|-------|
| Q53l          |    | Total |
| 0             | 67 |       |
| 1             | 43 |       |
| 2             | 38 |       |
| 3             | 12 |       |
| 4             | 9  |       |
| (blank)       |    |       |
| Grand Total   |    | 169   |

**Q53m Computing Industry**

Great benefit

Indifferent

No benefit

| Count of Q53m |    |       |
|---------------|----|-------|
| Q53m          |    | Total |
| 0             | 83 |       |
| 1             | 39 |       |
| 2             | 28 |       |
| 3             | 11 |       |
| 4             | 9  |       |
| (blank)       |    |       |
| Grand Total   |    | 170   |



## Summarised Data

### Question 1/2

|       | Male |     | Female |     | Total |
|-------|------|-----|--------|-----|-------|
| 16-24 | 64   | 37% | 8      | 5%  | 72    |
| 25-34 | 42   | 24% | 14     | 8%  | 56    |
| 35-49 | 26   | 15% | 8      | 5%  | 34    |
| 50-64 | 8    | 5%  | 4      | 2%  | 12    |
| Total | 140  | 80% | 34     | 20% | 174   |

### Question 11

|                         | Often | Occasionally | Never |
|-------------------------|-------|--------------|-------|
| Word Processing         | 115   | 28           | 6     |
| Spreadsheet             | 50    | 67           | 25    |
| Database                | 29    | 72           | 37    |
| Desktop Publishing      | 17    | 49           | 71    |
| Software Development    | 57    | 37           | 44    |
| Graphical Design        | 18    | 49           | 67    |
| Engineering/Scientific  | 44    | 47           | 45    |
| Web-browsing            | 88    | 39           | 18    |
| E-Mail                  | 113   | 20           | 14    |
| Games                   | 21    | 64           | 58    |
| Computer aided learning | 5     | 63           | 68    |

### Question 18

|                         | Often | Occasionally | Never |
|-------------------------|-------|--------------|-------|
| Word Processing         | 112   | 27           | 2     |
| Spreadsheet             | 42    | 67           | 25    |
| Database                | 17    | 56           | 52    |
| Desktop Publishing      | 22    | 47           | 57    |
| Software Development    | 37    | 52           | 39    |
| Graphical Design        | 26    | 46           | 57    |
| Engineering/Scientific  | 35    | 48           | 45    |
| Web-browsing            | 49    | 20           | 60    |
| E-Mail                  | 51    | 21           | 58    |
| Games                   | 56    | 54           | 27    |
| Computer aided learning | 6     | 40           | 81    |

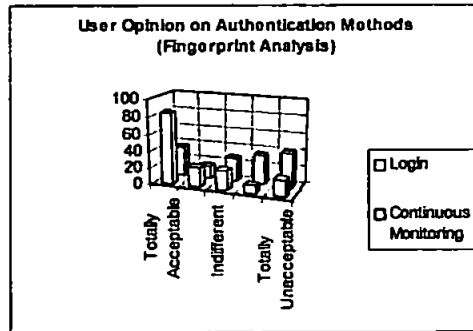
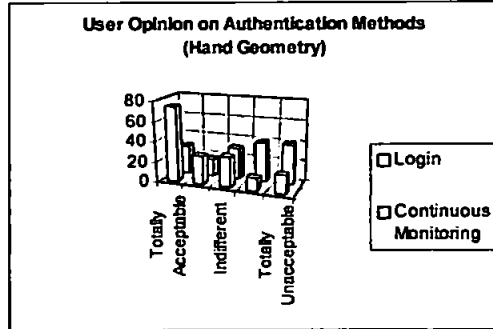
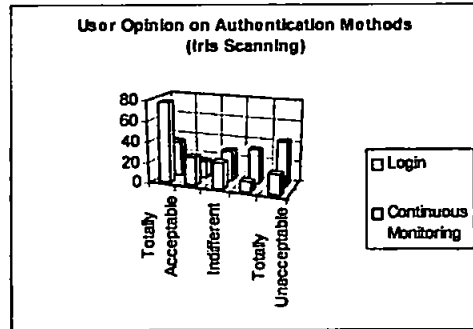
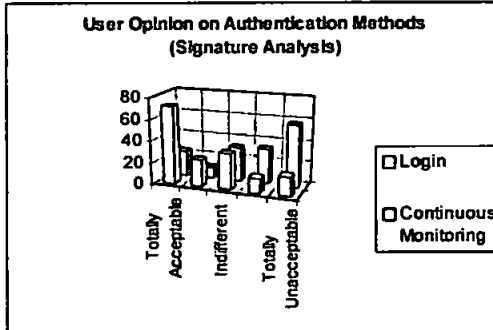
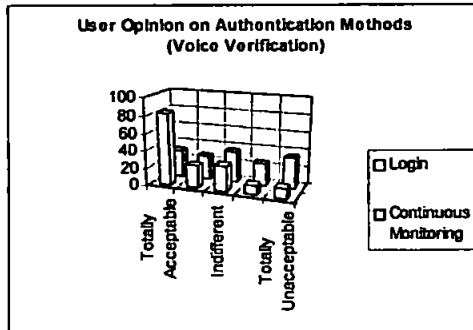
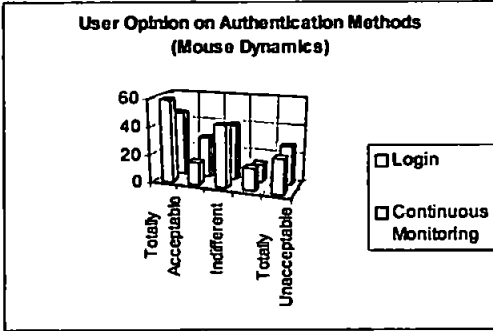
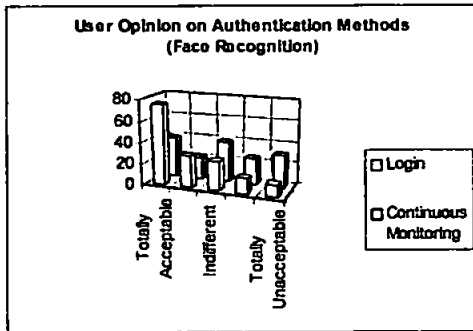
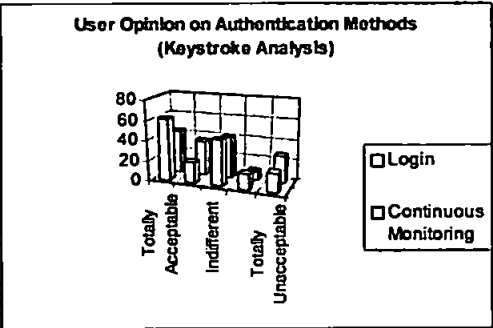
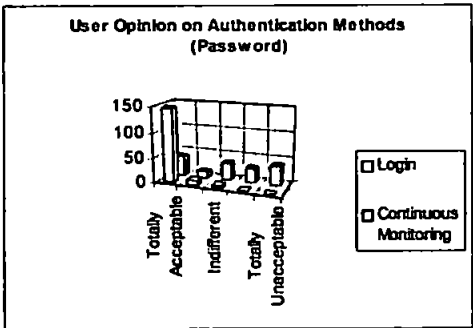
## Question 46

| Login                | Password   | Keystroke Analysis | Face Recognition | Mouse Dynamics | Voice Verification | Signature Analysis | Iris Scanning | Hand Geometry | Fingerprint Analysis |
|----------------------|------------|--------------------|------------------|----------------|--------------------|--------------------|---------------|---------------|----------------------|
| Totally Acceptable   | 148        | 61                 | 76               | 59             | 83                 | 72                 | 78            | 74            | 85                   |
| Acceptable           | 10         | 21                 | 30               | 16             | 26                 | 25                 | 28            | 28            | 24                   |
| Indifferent          | 5          | 45                 | 28               | 44             | 29                 | 33                 | 25            | 30            | 23                   |
| Unacceptable         | 1          | 15                 | 15               | 16             | 11                 | 14                 | 10            | 12            | 10                   |
| Totally Unacceptable | 0          | 19                 | 12               | 25             | 12                 | 18                 | 20            | 18            | 20                   |
| <b>Total</b>         | <b>164</b> | <b>161</b>         | <b>161</b>       | <b>160</b>     | <b>161</b>         | <b>162</b>         | <b>161</b>    | <b>162</b>    | <b>162</b>           |
|                      |            |                    |                  |                |                    |                    |               |               |                      |
| <b>Continuous</b>    |            |                    |                  |                |                    |                    |               |               |                      |
| Totally Acceptable   | 40         | 43                 | 39               | 46             | 32                 | 24                 | 34            | 29            | 36                   |
| Acceptable           | 13         | 35                 | 22               | 29             | 27                 | 10                 | 16            | 18            | 15                   |
| Indifferent          | 35         | 41                 | 39               | 40             | 36                 | 32                 | 29            | 31            | 29                   |
| Unacceptable         | 30         | 10                 | 25               | 13             | 25                 | 33                 | 33            | 39            | 35                   |
| Totally Unacceptable | 39         | 28                 | 31               | 28             | 35                 | 57                 | 43            | 39            | 41                   |
| <b>Total</b>         | <b>157</b> | <b>157</b>         | <b>156</b>       | <b>156</b>     | <b>155</b>         | <b>156</b>         | <b>155</b>    | <b>156</b>    | <b>156</b>           |
|                      |            |                    |                  |                |                    |                    |               |               |                      |
|                      |            |                    |                  |                |                    |                    |               |               |                      |
| <b>Login</b>         |            |                    |                  |                |                    |                    |               |               |                      |
| Acceptable           | 158        | 82                 | 106              | 75             | 109                | 97                 | 106           | 102           | 109                  |
| Unacceptable         | 1          | 34                 | 27               | 41             | 23                 | 32                 | 30            | 30            | 30                   |
| <b>Login</b>         | <b>157</b> | <b>48</b>          | <b>79</b>        | <b>34</b>      | <b>86</b>          | <b>65</b>          | <b>76</b>     | <b>72</b>     | <b>79</b>            |
|                      |            |                    |                  |                |                    |                    |               |               |                      |
| <b>Continuous</b>    |            |                    |                  |                |                    |                    |               |               |                      |
| Acceptable           | 53         | 78                 | 61               | 75             | 59                 | 34                 | 50            | 47            | 51                   |
| Unacceptable         | 69         | 38                 | 56               | 41             | 60                 | 90                 | 76            | 78            | 76                   |
| Continuous           | -16        | 40                 | 5                | 34             | -1                 | -56                | -26           | -31           | -25                  |

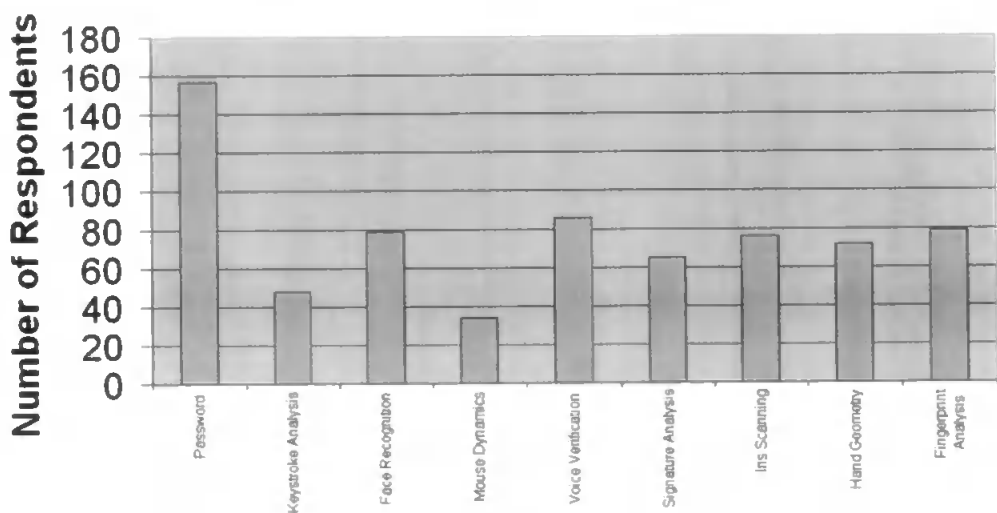
## Question 53

|               | Government | Defence | Education | Health | Social & Public Services | Banking, Finance & Insurance | Utility Services | Manufacturing | Engineering | Travel Industries and Tourism | Property Services | Communications Industry | Computing Industry |
|---------------|------------|---------|-----------|--------|--------------------------|------------------------------|------------------|---------------|-------------|-------------------------------|-------------------|-------------------------|--------------------|
| Great Benefit | 128        | 152     | 40        | 85     | 68                       | 129                          | 45               | 26            | 34          | 17                            | 27                | 67                      | 83                 |
| -             | 27         | 10      | 42        | 46     | 47                       | 27                           | 38               | 41            | 43          | 31                            | 33                | 43                      | 39                 |
| Indifferent   | 10         | 4       | 62        | 27     | 33                       | 9                            | 63               | 76            | 63          | 80                            | 79                | 38                      | 28                 |
| -             | 1          | 1       | 11        | 5      | 11                       | 3                            | 11               | 18            | 19          | 25                            | 15                | 12                      | 11                 |
| No Benefit    | 3          | 2       | 13        | 6      | 10                       | 0                            | 11               | 8             | 10          | 16                            | 15                | 9                       | 9                  |
|               |            |         |           |        |                          |                              |                  |               |             |                               |                   |                         |                    |
| Benefit       | 155        | 162     | 82        | 131    | 115                      | 156                          | 83               | 67            | 77          | 48                            | 60                | 110                     | 122                |
| No Benefit    | 4          | 3       | 24        | 11     | 21                       | 3                            | 22               | 26            | 29          | 41                            | 30                | 21                      | 20                 |
| Rank          | 151        | 159     | 58        | 120    | 94                       | 153                          | 61               | 41            | 48          | 7                             | 30                | 89                      | 102                |

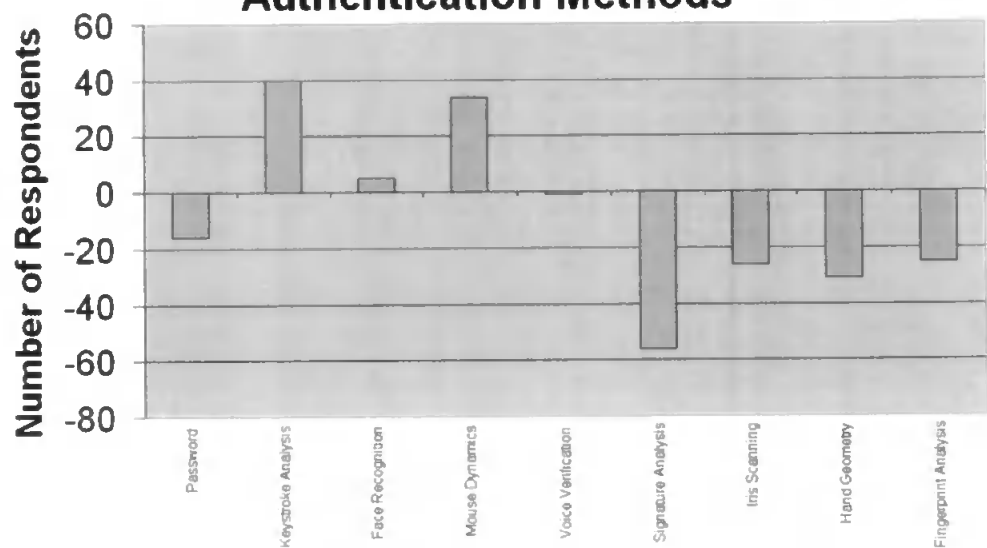
Additional Charts



User Preference for Login Authentication Methods



User Preference for Continuous Authentication Methods



## **Appendix B**

### ***Initial Trial Results***

## **Additional Trial Results**

This appendix contains additional material to support chapter 6. The first part of this appendix presents the summarised results for the initial trial, together with additional charts not included in the body of the thesis. The second part presents summarised results for the application-specific profiling, together with a selection of charts based upon these results.

## Trial Results

Comparison of reference profile against other user raw keylogger data

### Acceptance Rate

|        | User A | User B | User C | User D | User E | User H |
|--------|--------|--------|--------|--------|--------|--------|
| User A | 57     | 44     | 40     | 33     | 42     | 47     |
| User B | 46     | 52     | 41     | 36     | 41     | 42     |
| User C | 52     | 55     | 51     | 43     | 49     | 49     |
| User D | 23     | 32     | 29     | 47     | 26     | 30     |
| User E | 45     | 42     | 44     | 32     | 55     | 45     |
| User H | 46     | 41     | 38     | 35     | 41     | 55     |

### Cumulative Alert Level

|        | User A | User B | User C | User D | User E | User H |
|--------|--------|--------|--------|--------|--------|--------|
| User A | 332    | 6749   | 15376  | 18986  | 2355   | 17409  |
| User B | 11996  | 182    | 12485  | 14636  | 2441   | 53941  |
| User C | 507    | 67     | 182    | 7709   | 360    | 8790   |
| User D | 82163  | 19976  | 29543  | 3069   | 6369   | 125025 |
| User E | 11669  | 6402   | 6486   | 12713  | 42     | 22572  |
| User H | 15574  | 10501  | 18905  | 17125  | 2667   | 1750   |

### Highest Alert Level

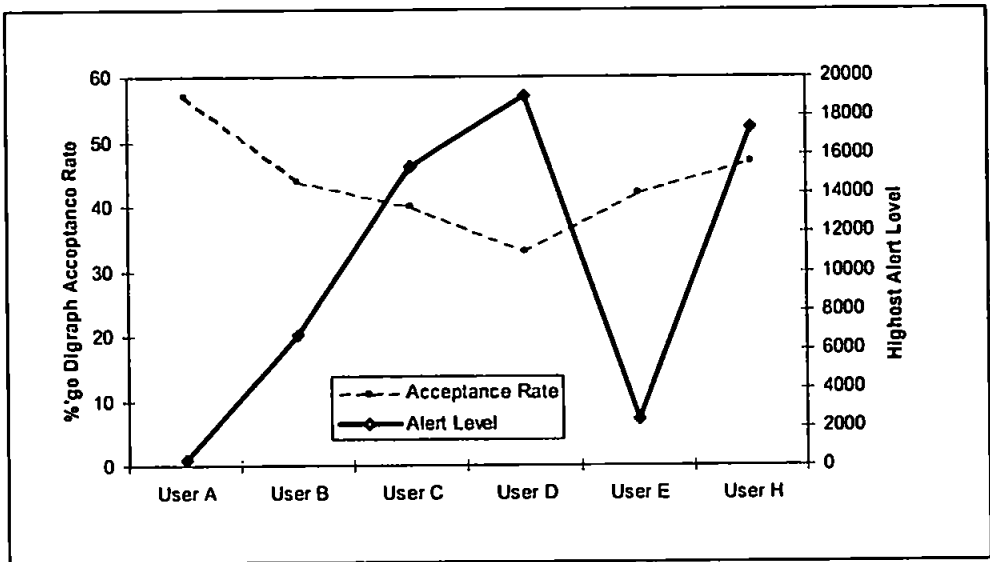
|        | User A | User B | User C | User D | User E | User H |
|--------|--------|--------|--------|--------|--------|--------|
| User A | 25     | 26     | 28     | 26     | 23     | 49     |
| User B | 43     | 16     | 28     | 34     | 19     | 119    |
| User C | 26     | 11     | 20     | 22     | 14     | 100    |
| User D | 60     | 28     | 38     | 19     | 23     | 36     |
| User E | 26     | 19     | 34     | 35     | 10     | 129    |
| User H | 29     | 21     | 34     | 25     | 15     | 64     |

### %ge Cumulative Alert Level

|        | User A | User B | User C | User D | User E | User H |
|--------|--------|--------|--------|--------|--------|--------|
| User A | 0.19   | 11.86  | 20.27  | 33.99  | 16.09  | 5.17   |
| User B | 7.88   | 0.33   | 17.36  | 27.86  | 17.8   | 17.1   |
| User C | 0.31   | 0.12   | 0.24   | 14.11  | 2.55   | 2.68   |
| User D | 54.32  | 36.91  | 41.36  | 5.54   | 47.24  | 39.67  |
| User E | 10.88  | 16.65  | 12.63  | 35.51  | 0.41   | 10.1   |
| User H | 8.94   | 17.87  | 24.12  | 29.62  | 17.62  | 0.51   |

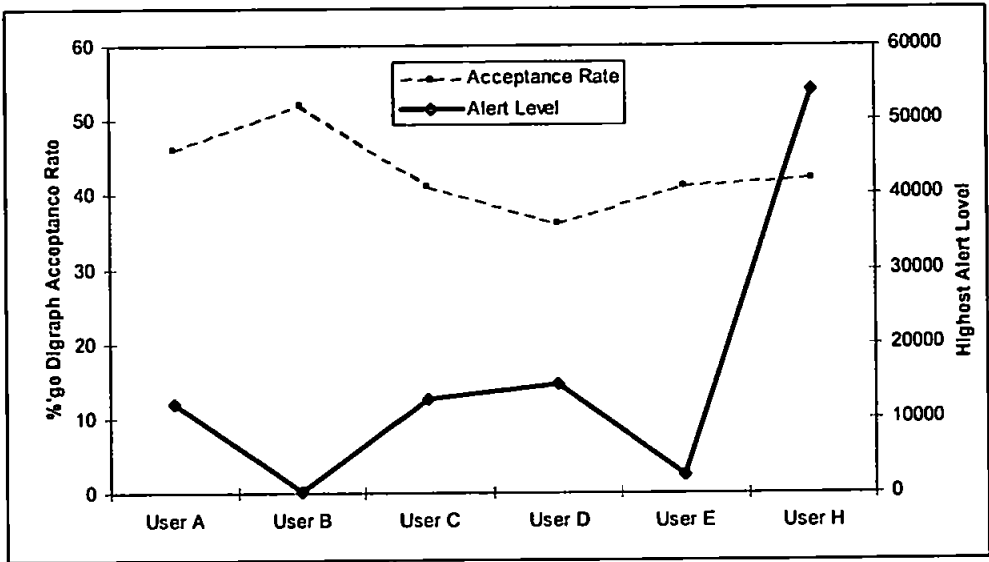


Reference Profile : User A



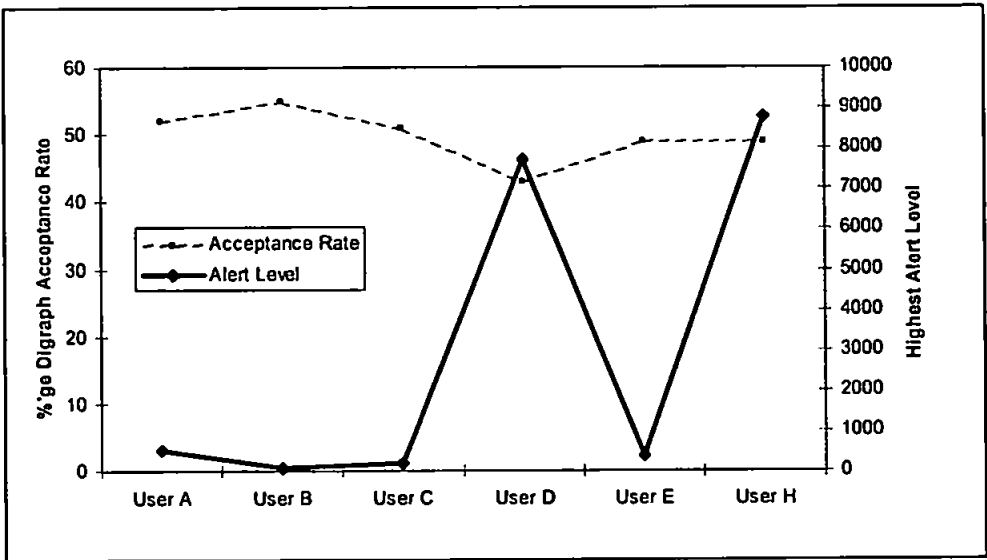
User A – 0% FRR, 0% FAR

Reference Profile : User B



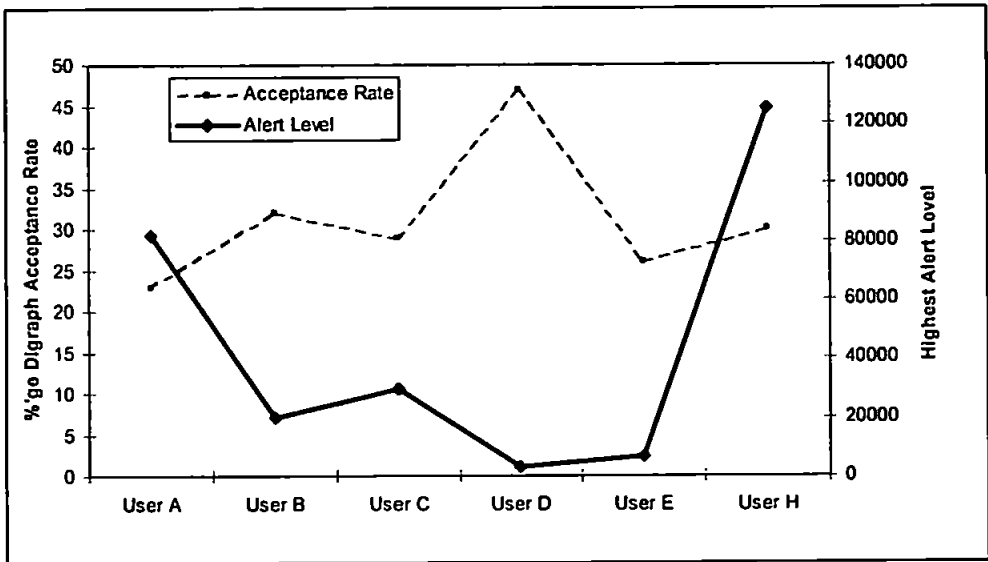
User B – 0% FRR, 0% FAR

Reference Profile : User C



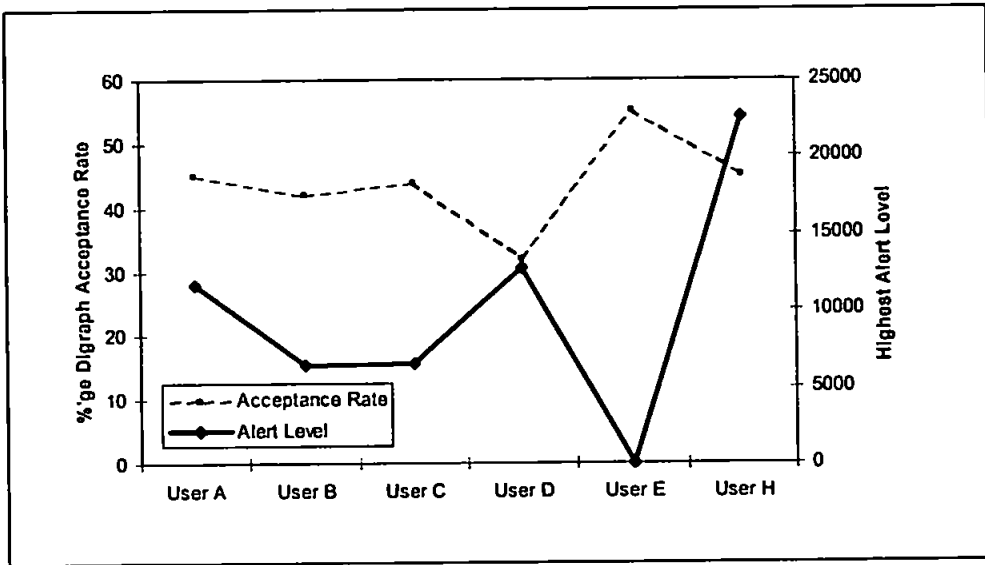
User C – 0% FRR, 3.3% FAR

Reference Profile : User D



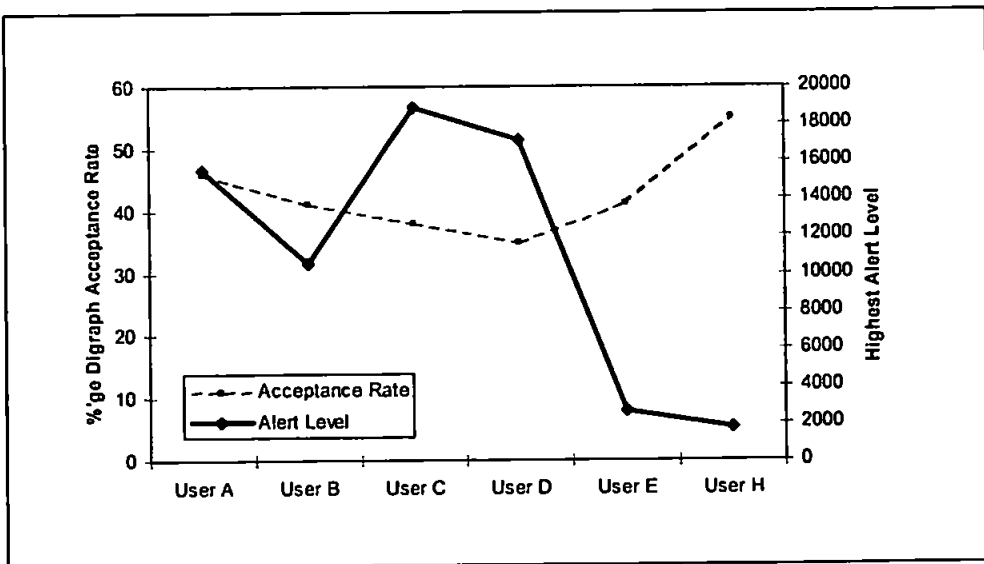
User D – 0% FRR, 0% FAR

Reference Profile : User E



User E – 0% FRR, 0% FAR

Reference Profile : User H



User H – 0% FRR, 0% FAR

## Application Specific Results

### Internet Explorer

Acceptance Rate (%)

|        | User A | User B | User C | User D | User H |
|--------|--------|--------|--------|--------|--------|
| User A | 56     | 42     | 38     | 27     | 22     |
| User B | 41     | 50     | 38     | 29     | 13     |
| User C | 56     | 57     | 53     | 44     | 18     |
| User D | 28     | 34     | 27     | 49     | 23     |
| User H | 17     | 10     | 10     | 17     | 50     |

### Outlook

Acceptance Rate (%)

|        | User B | User C | User D | User E | User H |
|--------|--------|--------|--------|--------|--------|
| User B | 54     | 40     | 37     | 39     | 43     |
| User C | 56     | 53     | 43     | 51     | 52     |
| User D | 33     | 30     | 48     | 27     | 33     |
| User E | 41     | 42     | 28     | 53     | 47     |
| User H | 39     | 38     | 36     | 44     | 61     |

### Word

Acceptance Rate (%)

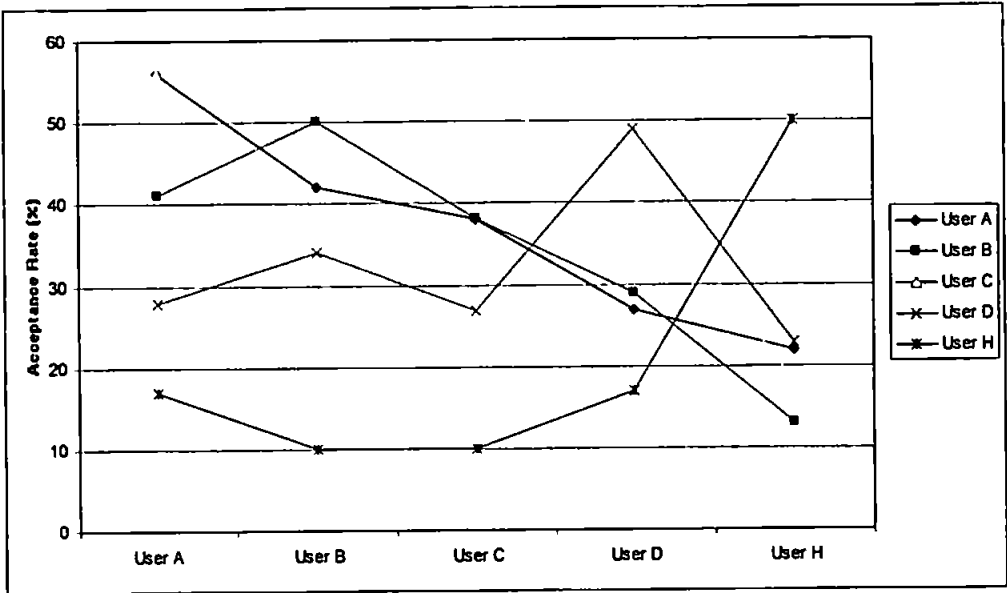
|        | User A | User B | User C | User D |
|--------|--------|--------|--------|--------|
| User A | 56     | 41     | 56     | 28     |
| User B | 42     | 50     | 57     | 34     |
| User C | 38     | 38     | 53     | 27     |
| User D | 27     | 29     | 44     | 49     |

### Summary

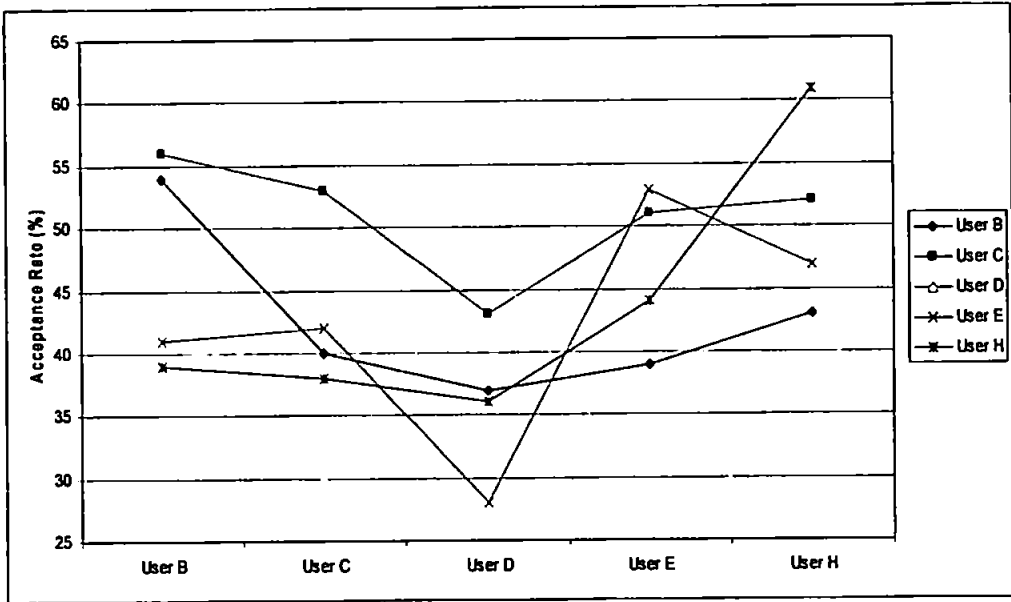
Acceptance Rate (%)

|           | User A | User B | User C | User D | User E | User F | User G | User H |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|
| ALL       | 57     | 52     | 51     | 47     | 55     | 52     | 60     | 55     |
| IE        | 55.4   | 51.1   | 50.6   | 49.1   | 50.8   | 52.5   | 60.3   | 20.3   |
| Messenger | 55.9   | 52.3   |        |        |        |        |        | 58.4   |
| Outlook   |        | 52.7   | 51.3   | 47.5   | 55.5   | 50.1   | 55.6   | 58.5   |
| Word      | 59.1   | 52.9   | 52.6   | 46.1   | 56.8   | 51.3   | 61.2   | 57.4   |

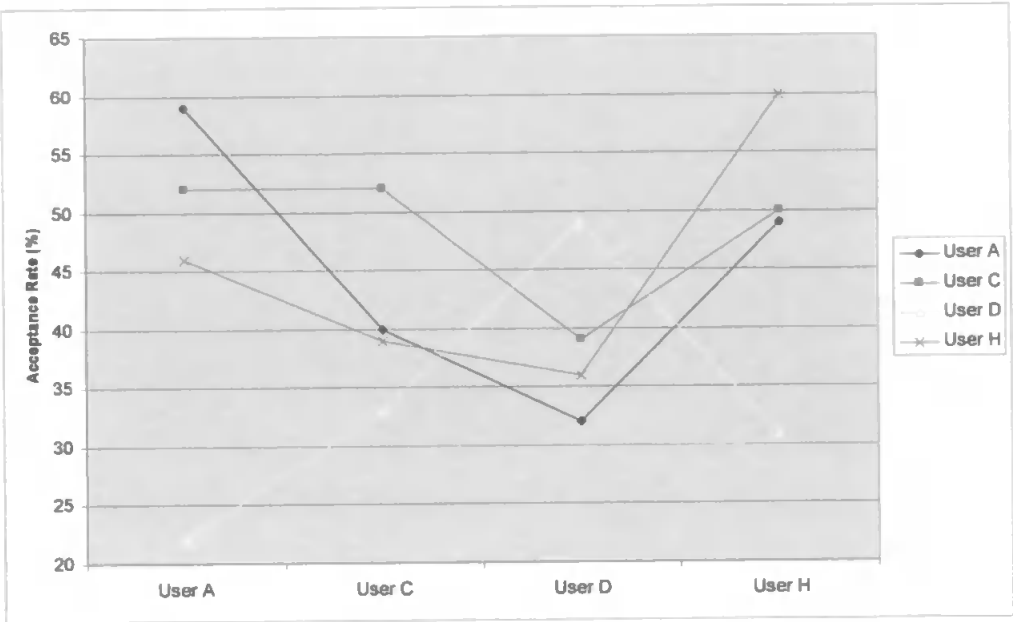
Internet Explorer Results



Outlook Results

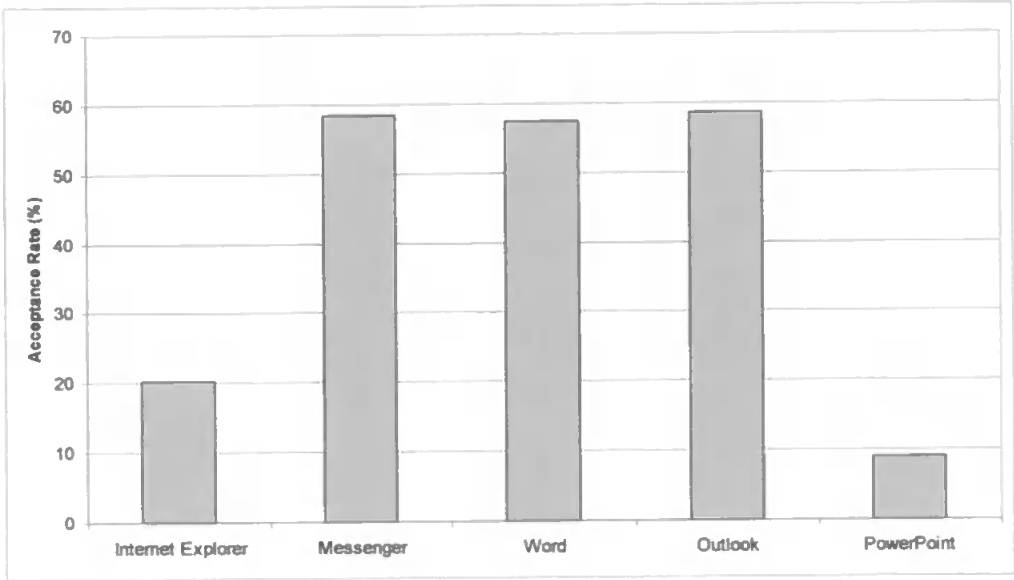


Word Results



Single User (H) Profile Comparisons

(raw keylogger data compared with specific application profiles)



# **Appendix C**

## ***Long-Term Trial Results***

## **Additional Trial Results**

This appendix contains additional material to support chapters 7 and 8. This appendix contains the list of keywords used for keyword latency monitoring. This appendix also includes the acceptance rate tables (in summarised form) for each of the main settings for digraph, trigraph and keyword. Finally, tables are presented summarising the effectiveness of the techniques by determining the number of keypresses required before an impostor (or the genuine user) is challenged. In all of these summarised tables, the reference profile is shown running across the table rows with the comparisons running vertically down the columns. Where the genuine user is compared against their own reference profile, the table cell is highlighted. For the challenge point tables (the last three) the optimum setting is achieved when there is a clear distinction between genuine users (with a high number of keypresses) and an impostor (with a low number of keypresses) indicating the number of keystrokes a user can press before the alert level generates a challenge. The other tables present the highest alert level of the system at various settings for the individual metrics and, as such, the aim is to obtain a low alert level for the genuine user and a high alert level for all impostors.



## Monitored keywords:

|          |           |           |           |          |
|----------|-----------|-----------|-----------|----------|
| word     | little    | number    | keep      | paper    |
| network  | very      | great     | children  | hard     |
| research | after     | tell      | feet      | near     |
| group    | words     | small     | land      | sentence |
| that     | called    | every     | side      | better   |
| with     | just      | found     | without   | best     |
| they     | where     | still     | once      | across   |
| this     | most      | between   | animals   | during   |
| from     | know      | name      | life      | today    |
| have     | through   | should    | enough    | others   |
| what     | back      | home      | took      | however  |
| were     | much      | give      | sometimes | sure     |
| when     | before    | line      | four      | means    |
| there    | good      | under     | head      | knew     |
| your     | write     | read      | above     | told     |
| which    | used      | last      | kind      | young    |
| their    | same      | never     | began     | miles    |
| said     | right     | left      | almost    | ways     |
| will     | look      | along     | live      | thing    |
| each     | think     | while     | page      | whole    |
| about    | also      | might     | earth     | hear     |
| them     | around    | next      | need      | example  |
| then     | another   | sound     | hand      | heard    |
| many     | came      | below     | high      | several  |
| some     | come      | something | year      | change   |
| these    | work      | thought   | mother    | answer   |
| would    | three     | both      | light     | room     |
| other    | word      | those     | parts     | against  |
| into     | must      | always    | country   | turned   |
| more     | because   | looked    | father    | three    |
| like     | does      | show      | night     | learn    |
| time     | part      | large     | following | point    |
| could    | even      | often     | picture   | city     |
| make     | place     | together  | being     | play     |
| than     | well      | asked     | study     | toward   |
| first    | such      | house     | second    | five     |
| been     | here      | don't     | eyes      | using    |
| people   | take      | world     | soon      | himself  |
| made     | things    | going     | times     | usually  |
| over     | help      | want      | story     |          |
| down     | years     | school    | boys      |          |
| only     | different | important | since     |          |
| find     | away      | until     | white     |          |
| water    | again     | form      | days      |          |
| long     | went      | food      | ever      |          |

[illegible]

| User    | Acceptance Count |      | 1180 Impositions |      | 35 Users |      | 5.1% |      | 0% Fixed |      | 5.1% |      |
|---------|------------------|------|------------------|------|----------|------|------|------|----------|------|------|------|
|         | FAR              | FRR  | FAR              | FRR  | FAR      | FRR  | FAR  | FRR  | FAR      | FRR  | FAR  | FRR  |
| User 1  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 2  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 3  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 4  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 5  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 6  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 7  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 8  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 9  | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 10 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 11 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 12 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 13 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 14 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 15 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 16 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 17 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 18 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 19 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 20 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 21 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 22 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 23 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 24 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 25 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 26 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 27 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 28 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 29 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 30 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 31 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 32 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 33 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 34 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |
| User 35 | 1180             | 1180 | 1180             | 1180 | 1180     | 1180 | 1180 | 1180 | 1180     | 1180 | 1180 | 1180 |



[illegible]





| 0.5 SD  | Reference Profiles | User 1 | User 2 | User 3 | User 4 | User 5 | User 6 | User 7 | User 8 | User 9 | User 10 | User 11 | User 12 | User 13 | User 14 | User 15 | User 16 | User 17 | User 18 | User 19 | User 20 | User 21 | User 22 | User 23 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 30 | User 31 | User 32 | User 33 | User 34 | User 35 |        |        |        |        |       |       |
|---------|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|--------|--------|--------|-------|-------|
| User 1  | 150508             | 24715  | 18824  | 24480  | 22382  | 24820  | 23887  | 22683  | 22665  | 21404  | 22355   | 23817   | 24390   | 23921   | 23014   | 24720   | 20278   | 24485   | 22759   | 25504   | 24684   | 20600   | 16286   | 16827   | 24577   | 24906   | 24072   | 21086   | 20004   | 24327   | 20387   | 23080   | 25228   | 22011   |         |         |        |        |        |        |       |       |
| User 2  | 37720              | 32816  | 37267  | 36998  | 37557  | 32591  | 36983  | 38517  | 36594  | 33306  | 39873   | 36307   | 39254   | 35888   | 37224   | 34941   | 40318   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011   | 31478   | 35011  |        |        |        |       |       |
| User 3  | 105173             | 123165 | 67769  | 100945 | 106434 | 100945 | 106434 | 100945 | 106434 | 100945 | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434  | 100945  | 106434 |        |        |        |       |       |
| User 4  | 18351              | 35158  | 20862  | 36068  | 33541  | 38125  | 35311  | 34947  | 34947  | 34947  | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947  |        |        |        |       |       |
| User 5  | 35102              | 35158  | 20862  | 36068  | 33541  | 38125  | 35311  | 34947  | 34947  | 34947  | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947   | 34947  | 34947  |        |        |       |       |
| User 6  | 34920              | 37850  | 32987  | 35008  | 34588  | 33081  | 33855  | 34480  | 35516  | 33228  | 34172   | 31299   | 33074   | 34650   | 33781   | 30427   | 30816   | 32548   | 32884   | 31578   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880   | 31880  | 31880  | 31880  |        |       |       |
| User 7  | 34941              | 35946  | 31329  | 38930  | 34510  | 35332  | 33076  | 35028  | 35553  | 36020  | 30381   | 35404   | 34441   | 34340   | 35182   | 35788   | 34354   | 35800   | 31884   | 34359   | 34563   | 28820   | 28598   | 16882   | 16817   | 30175   | 38977   | 34786   | 33575   | 32978   | 35578   | 33432   | 31886   | 28925   | 35908   | 30749   |        |        |        |        |       |       |
| User 8  | 21520              | 25824  | 19246  | 25803  | 23852  | 24445  | 21947  | 24712  | 23193  | 26590  | 23533   | 25107   | 25174   | 24882   | 24885   | 25733   | 23135   | 25038   | 31418   | 26289   | 23781   | 27865   | 16882   | 16817   | 30175   | 38977   | 34786   | 33575   | 32978   | 35578   | 33432   | 31886   | 28925   | 35908   | 30749   |         |        |        |        |        |       |       |
| User 9  | 142555             | 189653 | 198129 | 151334 | 148528 | 148528 | 148528 | 148528 | 148528 | 148528 | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528 | 148528 | 148528 |        |       |       |
| User 10 | 48820              | 49344  | 49335  | 51277  | 48153  | 48170  | 44530  | 45707  | 50480  | 47810  | 47103   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230   | 47230  | 47230  | 47230  |        |       |       |
| User 11 | 142555             | 189653 | 198129 | 151334 | 148528 | 148528 | 148528 | 148528 | 148528 | 148528 | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528  | 148528 | 148528 | 148528 | 148528 |       |       |
| User 12 | 44338              | 13809  | 14918  | 14780  | 14888  | 13868  | 14919  | 14408  | 14425  | 14414  | 13333   | 13123   | 13854   | 13861   | 14148   | 13868   | 15562   | 12519   | 14910   | 14572   | 14359   | 14749   | 13868   | 16286   | 16827   | 24577   | 24906   | 24072   | 21086   | 20004   | 24327   | 20387   | 23080   | 25228   | 22011   |         |        |        |        |        |       |       |
| User 13 | 44300              | 42768  | 11815  | 44584  | 42985  | 42985  | 41800  | 43809  | 44250  | 42748  | 37125   | 36297   | 42300   | 43074   | 43815   | 44187   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871   | 42165   | 42871  | 42165  | 42871  | 42165  |       |       |
| User 14 | 22084              | 24065  | 20069  | 24401  | 22529  | 23810  | 23810  | 21107  | 22818  | 23346  | 17296   | 23297   | 23030   | 21313   | 22927   | 21494   | 24081   | 20380   | 21411   | 22137   | 22685   | 18984   | 23717   | 24284   | 24580   | 29437   | 29540   | 30108   | 30228   | 28433   | 35841   | 37194   | 18512   | 23180   | 23087   |         |        |        |        |        |       |       |
| User 15 | 10453              | 11276  | 10359  | 11781  | 10841  | 11150  | 10873  | 10870  | 10915  | 10246  | 6888    | 11429   | 10705   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743   | 10254   | 10743  | 10254  | 10743  | 10254  |       |       |
| User 16 | 86270              | 70806  | 62397  | 70386  | 68771  | 70113  | 69572  | 70113  | 69572  | 70113  | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572   | 70113   | 69572  | 70113  | 69572  | 70113  |       |       |
| User 17 | 50988              | 81076  | 81076  | 81076  | 81076  | 81076  | 81076  | 81076  | 81076  | 81076  | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076   | 81076  | 81076  | 81076  | 81076  |       |       |
| User 18 | 70588              | 73845  | 61425  | 73719  | 73151  | 73407  | 70784  | 70110  | 71581  | 73210  | 62705   | 71805   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651  | 69651  | 69651  | 69651  |       |       |
| User 19 | 53288              | 53822  | 61425  | 68346  | 58281  | 52301  | 48373  | 48373  | 48373  | 48373  | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373   | 48373  | 48373  | 48373  | 48373  |       |       |
| User 20 | 50988              | 52805  | 51737  | 58001  | 58552  | 58001  | 51784  | 52810  | 79450  | 84558  | 70253   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651  | 69651  | 69651  | 69651  | 69651 |       |
| User 21 | 14781              | 63017  | 63432  | 63123  | 70400  | 61967  | 73784  | 72310  | 79450  | 84558  | 70253   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651   | 69651  | 69651  | 69651  | 69651  | 69651 |       |
| User 22 | 73588              | 70034  | 68645  | 78518  | 78184  | 78537  | 78243  | 78817  | 77715  | 81025  | 78708   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575   | 77575  | 77575  | 77575  | 77575  | 77575 |       |
| User 23 | 123881             | 138848 | 110888 | 138102 | 126884 | 137284 | 13154  | 127880 | 128576 | 144158 | 129633  | 134317  | 138609  | 135653  | 132440  | 138488  | 117888  | 137444  | 124288  | 138658  | 142753  | 128653  | 133068  | 130108  | 133880  | 141332  | 143453  | 145850  | 137259  | 13253   | 103816  | 84182   | 134537  | 141975  | 128358  |         |        |        |        |        |       |       |
| User 24 | 27173              | 25880  | 30477  | 27188  | 27489  | 26127  | 25983  | 27083  | 27680  | 28212  | 27758   | 28078   | 28207   | 28719   | 27111   | 25512   | 29786   | 24413   | 28103   | 28891   | 27088   | 30434   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384   | 23384  | 23384  | 23384  | 23384  | 23384 |       |
| User 25 | 34629              | 31130  | 34333  | 35270  | 31980  | 37023  | 34558  | 35394  | 31984  | 33781  | 33389   | 31548   | 33827   | 34541   | 31622   | 37550   | 26521   | 35881   | 34515   | 32579   | 38242   | 34118   | 42094   | 33296   | 23941   | 34505   | 35878   | 38242   | 34118   | 42094   | 33296   | 23941   | 34505   | 35878   | 38242   | 34118   | 42094  | 33296  | 23941  | 34505  | 35878 | 38242 |
| User 26 | 22311              | 23947  | 20394  | 23988  | 22822  | 23984  | 21012  | 21688  | 22558  | 23985  | 19888   | 25402   | 22840   | 21589   | 22288   | 23832   | 23824   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868   | 22868  | 22868  | 22868  | 22868  | 22868 | 22868 |
| User 27 | 46423              | 48149  | 38873  | 47835  | 48810  | 47687  | 47140  | 48171  | 48308  | 48740  | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308   | 48740   | 48308  | 48740  | 48308  | 48740  | 48308 |       |
| User 28 | 53408              | 57885  | 47212  | 57881  | 53944  | 57212  | 54189  | 52857  | 54389  | 58945  | 53435   | 56304   | 55969   | 53705   | 54384   | 57074   | 52201   | 56783   | 50748   | 57187   | 57283   | 47271   | 44781   | 47574   | 37978   | 58491   | 54537   | 50165   | 45127   | 57001   | 43857   | 39728   | 50682   | 68748   | 44987   |         |        |        |        |        |       |       |
| User 29 | 29078              | 28515  | 30079  | 29590  | 29308  | 28200  | 29484  | 29012  | 29448  | 28171  | 27821   | 28859   | 28110   | 28933   | 28859   | 28778   | 30653   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778   | 28859   | 28778  | 28859  | 28778  | 28859  | 28778 | 28859 |
| User 30 | 189331             | 227288 | 140118 | 228625 | 183083 | 228788 | 205858 | 188831 | 193880 | 231284 | 204483  | 2       |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |        |        |        |        |       |       |



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| 0 to 50 |     | 50 to 100 |     | 100 to 150 |     | 150 to 200 |     | 200 to 250 |     | 250 to 300 |     | 300 to 350 |     | 350 to 400 |     | 400 to 450 |     | 450 to 500 |     | 500 to 550 |     | 550 to 600 |     | 600 to 650 |     | 650 to 700 |     | 700 to 750 |     | 750 to 800 |     | 800 to 850 |     | 850 to 900 |     | 900 to 950 |     | 950 to 1000 |     | 1000 to 1050 |     | 1050 to 1100 |     | 1100 to 1150 |     | 1150 to 1200 |     | 1200 to 1250 |     | 1250 to 1300 |     | 1300 to 1350 |     | 1350 to 1400 |     | 1400 to 1450 |     | 1450 to 1500 |     | 1500 to 1550 |     | 1550 to 1600 |     | 1600 to 1650 |     | 1650 to 1700 |     | 1700 to 1750 |     | 1750 to 1800 |     | 1800 to 1850 |     | 1850 to 1900 |     | 1900 to 1950 |     | 1950 to 2000 |     | 2000 to 2050 |     | 2050 to 2100 |     | 2100 to 2150 |     | 2150 to 2200 |     | 2200 to 2250 |     | 2250 to 2300 |     | 2300 to 2350 |     | 2350 to 2400 |     | 2400 to 2450 |     | 2450 to 2500 |     | 2500 to 2550 |     | 2550 to 2600 |     | 2600 to 2650 |     | 2650 to 2700 |     | 2700 to 2750 |     | 2750 to 2800 |     | 2800 to 2850 |     | 2850 to 2900 |     | 2900 to 2950 |     | 2950 to 3000 |     | 3000 to 3050 |     | 3050 to 3100 |     | 3100 to 3150 |     | 3150 to 3200 |     | 3200 to 3250 |     | 3250 to 3300 |     | 3300 to 3350 |     | 3350 to 3400 |     | 3400 to 3450 |     | 3450 to 3500 |     | 3500 to 3550 |     | 3550 to 3600 |     | 3600 to 3650 |     | 3650 to 3700 |     | 3700 to 3750 |     | 3750 to 3800 |     | 3800 to 3850 |     | 3850 to 3900 |     | 3900 to 3950 |     | 3950 to 4000 |     | 4000 to 4050 |     | 4050 to 4100 |     | 4100 to 4150 |     | 4150 to 4200 |     | 4200 to 4250 |     | 4250 to 4300 |     | 4300 to 4350 |     | 4350 to 4400 |     | 4400 to 4450 |     | 4450 to 4500 |     | 4500 to 4550 |     | 4550 to 4600 |     | 4600 to 4650 |     | 4650 to 4700 |     | 4700 to 4750 |     | 4750 to 4800 |     | 4800 to 4850 |     | 4850 to 4900 |     | 4900 to 4950 |     | 4950 to 5000 |     | 5000 to 5050 |     | 5050 to 5100 |     | 5100 to 5150 |     | 5150 to 5200 |     | 5200 to 5250 |     | 5250 to 5300 |     | 5300 to 5350 |     | 5350 to 5400 |     | 5400 to 5450 |     | 5450 to 5500 |     | 5500 to 5550 |     | 5550 to 5600 |     | 5600 to 5650 |     | 5650 to 5700 |     | 5700 to 5750 |     | 5750 to 5800 |     | 5800 to 5850 |     | 5850 to 5900 |     | 5900 to 5950 |     | 5950 to 6000 |     | 6000 to 6050 |     | 6050 to 6100 |     | 6100 to 6150 |     | 6150 to 6200 |     | 6200 to 6250 |     | 6250 to 6300 |     | 6300 to 6350 |     | 6350 to 6400 |     | 6400 to 6450 |     | 6450 to 6500 |     | 6500 to 6550 |     | 6550 to 6600 |     | 6600 to 6650 |     | 6650 to 6700 |     | 6700 to 6750 |     | 6750 to 6800 |     | 6800 to 6850 |     | 6850 to 6900 |     | 6900 to 6950 |     | 6950 to 7000 |     | 7000 to 7050 |     | 7050 to 7100 |     | 7100 to 7150 |     | 7150 to 7200 |     | 7200 to 7250 |     | 7250 to 7300 |     | 7300 to 7350 |     | 7350 to 7400 |     | 7400 to 7450 |     | 7450 to 7500 |     | 7500 to 7550 |     | 7550 to 7600 |     | 7600 to 7650 |     | 7650 to 7700 |     | 7700 to 7750 |     | 7750 to 7800 |     | 7800 to 7850 |     | 7850 to 7900 |     | 7900 to 7950 |     | 7950 to 8000 |     | 8000 to 8050 |     | 8050 to 8100 |     | 8100 to 8150 |     | 8150 to 8200 |     | 8200 to 8250 |     | 8250 to 8300 |     | 8300 to 8350 |     | 8350 to 8400 |     | 8400 to 8450 |     | 8450 to 8500 |     | 8500 to 8550 |     | 8550 to 8600 |     | 8600 to 8650 |     | 8650 to 8700 |     | 8700 to 8750 |     | 8750 to 8800 |     | 8800 to 8850 |     | 8850 to 8900 |     | 8900 to 8950 |     | 8950 to 9000 |     | 9000 to 9050 |     | 9050 to 9100 |     | 9100 to 9150 |     | 9150 to 9200 |     | 9200 to 9250 |     | 9250 to 9300 |     | 9300 to 9350 |     | 9350 to 9400 |     | 9400 to 9450 |     | 9450 to 9500 |     | 9500 to 9550 |     | 9550 to 9600 |     | 9600 to 9650 |     | 9650 to 9700 |     | 9700 to 9750 |     | 9750 to 9800 |     | 9800 to 9850 |     | 9850 to 9900 |     | 9900 to 9950 |     | 9950 to 10000 |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |     |      |
|---------|-----|-----------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|-------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|--------------|-----|---------------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|-----|------|
| Unit    | Ref | Unit      | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit       | Ref | Unit        | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit         | Ref | Unit          | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit | Ref | Unit |

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|---------|--------|--------------------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-------|-----|----|
| 77      | SD     | Reference Profiles |        |        |        |        |        |        |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |       |     |    |
| User 1  | User 2 | User 3             | User 4 | User 5 | User 6 | User 7 | User 8 | User 9 | User 10 | User 11 | User 12 | User 13 | User 14 | User 15 | User 16 | User 17 | User 18 | User 19 | User 20 | User 21 | User 22 | User 23 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 30 | User 31 | User 32 | User 33 | User 34 | User 35 |       |     |    |
| 50      | 21     | 72                 | 22     | 22     | 22     | 50     | 24     | 24     | 38      | 31      | 23      | 22      | 22      | 21      | 21      | 66      | 33      | 43      | 22      | 19      | 94      | 116     | 52      | 16      | 18      | 21      | 40      | 41      | 52      | 21      | 16      | 93      | 135     | 16      | 106   |     |    |
| User 2  | 28     | 5306               | 23     | 18     | 26     | 260    | 65     | 28     | 320     | 5306    | 26      | 5306    | 57      | 54      | 50      | 125     | 5306    | 78      | 321     | 64      | 27      | 127     | 73      | 49      | 18      | 27      | 24      | 54      | 120     | 21      | 16      | 93      | 135     | 16      | 106   |     |    |
| User 3  | 30     | 15                 | 139718 | 18     | 26     | 22     | 22     | 20     | 30      | 20      | 14      | 28      | 17      | 21      | 21      | 127     | 14      | 28      | 15      | 64      | 50      | 88      | 79      | 15      | 18      | 27      | 24      | 54      | 120     | 21      | 16      | 93      | 135     | 16      | 106   |     |    |
| User 4  | 22     | 68                 | 15     | 350    | 13     | 37     | 18     | 23     | 19      | 55      | 22      | 22      | 27      | 53      | 32      | 32      | 32      | 145     | 17      | 18      | 28      | 18      | 63      | 15      | 80      | 88      | 79      | 15      | 18      | 27      | 24      | 54      | 120     | 21      | 106   |     |    |
| User 5  | 25     | 31                 | 34     | 18     | 73     | 31     | 31     | 30     | 35      | 32      | 22      | 22      | 27      | 29      | 29      | 145     | 17      | 18      | 28      | 15      | 64      | 50      | 88      | 79      | 15      | 18      | 27      | 24      | 54      | 120     | 21      | 16      | 93      | 135     | 16    | 106 |    |
| User 6  | 18     | 54                 | 28     | 22     | 22     | 43     | 18     | 23     | 30      | 347     | 23      | 158     | 20      | 32      | 32      | 32      | 44      | 3435    | 77      | 104     | 63      | 58      | 76      | 17      | 28      | 28      | 39      | 39      | 34      | 24      | 73      | 29      | 74      | 124     | 50622 | 30  | 34 |
| User 7  | 43     | 101                | 372    | 27     | 145    | 108    | 76576  | 54     | 50      | 39      | 76576   | 53      | 247     | 42      | 38      | 38      | 72      | 60      | 76576   | 76576   | 76576   | 76576   | 2188    | 18      | 28      | 28      | 39      | 39      | 39      | 39      | 39      | 39      | 39      | 39      | 39    | 39  |    |
| User 8  | 21     | 30                 | 27     | 26     | 25     | 38     | 25     | 38     | 25      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27    |     |    |
| User 9  | 46     | 15                 | 116    | 19     | 45     | 28     | 40     | 40     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105     | 105   | 105 |    |
| User 10 | 23     | 22                 | 20     | 18     | 17     | 23     | 38     | 38     | 144     | 227080  | 83      | 117     | 28      | 21      | 21      | 32      | 22      | 41      | 40      | 48      | 41      | 28      | 20      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22    | 22  |    |
| User 11 | 20     | 84                 | 25     | 17     | 19     | 88     | 13     | 63     | 16      | 144     | 227080  | 43      | 117     | 28      | 21      | 32      | 22      | 41      | 40      | 48      | 41      | 28      | 20      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22    | 22  |    |
| User 12 | 20     | 103                | 42     | 33     | 27     | 102    | 40     | 40     | 15      | 30      | 265     | 33      | 107     | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30    |     |    |
| User 13 | 24     | 31                 | 24     | 33     | 27     | 41     | 23     | 40     | 15      | 30      | 265     | 33      | 107     | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30    |     |    |
| User 14 | 38     | 33                 | 10     | 18     | 20     | 35     | 34     | 64     | 40      | 182     | 31039   | 20      | 40      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32    |     |    |
| User 15 | 17     | 44                 | 12     | 12     | 12     | 20     | 20     | 20     | 15      | 17      | 15861   | 19      | 15      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18    |     |    |
| User 16 | 10     | 42339              | 17     | 21     | 18     | 37     | 17     | 40     | 1065    | 42      | 43      | 42339   | 39      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40      | 40    |     |    |
| User 17 | 33     | 21                 | 85     | 24     | 51     | 33     | 89     | 63     | 53      | 17      | 15      | 28      | 144     | 32      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48    |     |    |
| User 18 | 32     | 28                 | 51     | 25     | 31     | 32     | 59     | 47     | 17      | 15      | 28      | 144     | 32      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48    |     |    |
| User 19 | 23     | 38                 | 121    | 21     | 31     | 32     | 59     | 47     | 17      | 15      | 28      | 144     | 32      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48      | 48    |     |    |
| User 20 | 21     | 67                 | 54     | 20     | 34     | 64     | 64     | 64     | 64      | 76576   | 21      | 102     | 81      | 38      | 28      | 64      | 84      | 3444    | 189     | 211     | 80620   | 131     | 121     | 47      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32      | 32    | 32  |    |
| User 21 | 19     | 2555               | 38     | 22     | 39     | 200    | 100    | 129    | 25      | 80026   | 48      | 2850    | 89      | 22      | 18      | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315     | 30      | 315   |     |    |
| User 22 | 28     | 32                 | 1160   | 18     | 29     | 90     | 28     | 28     | 21      | 20      | 29      | 30      | 343     | 23      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30    |     |    |
| User 23 | 20     | 31                 | 14     | 20     | 16     | 20     | 14     | 21     | 20      | 29      | 30      | 343     | 23      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30    |     |    |
| User 24 | 45     | 16                 | 902    | 14     | 34     | 48     | 45     | 45     | 15      | 15      | 22      | 39      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18    |     |    |
| User 25 | 19     | 14                 | 13     | 24     | 18     | 18     | 13     | 17     | 15      | 22      | 39      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18    |     |    |
| User 26 | 16     | 18023              | 15     | 38     | 37     | 182    | 20     | 56     | 22      | 56      | 1857    | 64      | 902     | 31      | 29      | 458     | 38      | 48488   | 65      | 158     | 417     | 56      | 146     | 21      | 13      | 13      | 13      | 13      | 13      | 13      | 13      | 13      | 13      | 13      | 13    |     |    |
| User 27 | 27     | 20                 | 70217  | 17     | 17     | 38     | 33     | 40     | 41      | 25      | 29      | 19      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18      | 18    |     |    |
| User 28 | 27     | 32                 | 58     | 20     | 27     | 24     | 33     | 33     | 17      | 17      | 33      | 35      | 20      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      | 24      |         |         |         |         |         |         |       |     |    |

10010666  
2400438  
7604520  
8741  
80215

Total keypresses before challenge across all profiles  
Total keypresses before challenge against valid user  
Total keypresses before challenge against impostor  
Average keypresses before challenge - Invalid user  
Average keypresses before valid user challenged

| Reference Profiles |        |        | Keyphrase until challenge - composite |        |        | Alert Threshold = 70 |        |        | Dygraph = 0.7SD no unmatched alert increase |         |         | Taygraph = 0.6SD unmatched alert increase |         |         | Words 0.6SD |         |         | Starting alert=50 |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |  |  |  |  |
|--------------------|--------|--------|---------------------------------------|--------|--------|----------------------|--------|--------|---------------------------------------------|---------|---------|-------------------------------------------|---------|---------|-------------|---------|---------|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--|--|--|--|
| User 1             | User 2 | User 3 | User 4                                | User 5 | User 6 | User 7               | User 8 | User 9 | User 10                                     | User 11 | User 12 | User 13                                   | User 14 | User 15 | User 16     | User 17 | User 18 | User 19           | User 20 | User 21 | User 22 | User 23 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 30 | User 31 | User 32 | User 33 | User 34 | User 35 |  |  |  |  |
| 51                 | 200    | 24     | 27                                    | 23     | 29     | 31                   | 18     | 18     | 17                                          | 28      | 38      | 35                                        | 31      | 38      | 52          | 28      | 24      | 26                | 81      | 42      | 47      | 52      | 20      | 62      | 19      | 38      | 30      | 32      | 25      | 44      | 29      | 38      | 38      |         |  |  |  |  |
| 42                 | 200    | 24     | 27                                    | 23     | 29     | 31                   | 33     | 37     | 48                                          | 32      | 22      | 29                                        | 39      | 32      | 32          | 264     | 64      | 64                | 81      | 47      | 52      | 20      | 62      | 19      | 38      | 30      | 32      | 25      | 44      | 29      | 38      | 38      |         |         |  |  |  |  |
| 46                 | 30     | 47     | 31                                    | 31     | 32     | 35                   | 35     | 101    | 48                                          | 202     | 39      | 29                                        | 39      | 32      | 32          | 264     | 64      | 64                | 81      | 47      | 52      | 20      | 62      | 19      | 38      | 30      | 32      | 25      | 44      | 29      | 38      | 38      |         |         |  |  |  |  |
| 30                 | 27     | 16     | 35                                    | 28     | 20     | 29                   | 17     | 17     | 17                                          | 30      | 22      | 28                                        | 35      | 32      | 32          | 26      | 4       | 20                | 17      | 28      | 17      | 23      | 39      | 29      | 17      | 12      | 16      | 16      | 26      | 30      | 26      | 30      |         |         |  |  |  |  |
| 19                 | 17     | 24     | 14                                    | 19     | 24     | 24                   | 22     | 16     | 31                                          | 35      | 24      | 38                                        | 27      | 23      | 41          | 20      | 35      | 34                | 66      | 37      | 24      | 14      | 17      | 23      | 39      | 29      | 17      | 12      | 16      | 26      | 30      | 26      | 30      |         |  |  |  |  |
| 24                 | 33     | 17     | 21                                    | 23     | 25     | 38                   | 30     | 16     | 35                                          | 109     | 35      | 37                                        | 35      | 35      | 24          | 29      | 38      | 42                | 50      | 32      | 13      | 26      | 14      | 33      | 30      | 52      | 16      | 20      | 39      | 13      | 424     | 37      | 13      |         |  |  |  |  |
| 35                 | 30     | 37     | 29                                    | 63     | 31     | 30                   | 102    | 33     | 42                                          | 31      | 33      | 35                                        | 37      | 38      | 24          | 29      | 38      | 42                | 50      | 32      | 13      | 26      | 14      | 33      | 30      | 52      | 16      | 20      | 39      | 13      | 424     | 37      | 13      |         |  |  |  |  |
| 38                 | 28     | 24     | 18                                    | 29     | 30     | 36                   | 88     | 20     | 16                                          | 30      | 21      | 47                                        | 27      | 27      | 24          | 27      | 50      | 34                | 64      | 33      | 294     | 207     | 47      | 23      | 29      | 34      | 30      | 52      | 16      | 20      | 39      | 13      | 424     |         |  |  |  |  |
| 21                 | 19     | 30     | 21                                    | 14     | 19     | 37                   | 16     | 37     | 16                                          | 37      | 16      | 37                                        | 16      | 37      | 16          | 37      | 16      | 37                | 16      | 37      | 16      | 37      | 16      | 37      | 16      | 37      | 16      | 37      | 16      | 37      | 16      | 37      | 16      | 37      |  |  |  |  |
| 20                 | 27     | 10     | 18                                    | 13     | 14     | 34                   | 31     | 16     | 48                                          | 39      | 28      | 27                                        | 23      | 39      | 18          | 11      | 28      | 14                | 18      | 16      | 23      | 12      | 13      | 20      | 30      | 11      | 11      | 30      | 11      | 12      | 33      | 30      | 33      |         |  |  |  |  |
| 40                 | 50     | 18     | 23                                    | 40     | 38     | 45                   | 73     | 16     | 62                                          | 1187    | 39      | 34                                        | 64      | 57      | 40          | 48      | 38      | 48                | 64      | 73      | 73      | 34      | 30      | 34      | 37      | 44      | 20      | 29      | 70      | 27      | 67      | 53      | 35      |         |  |  |  |  |
| 41                 | 34     | 29     | 20                                    | 26     | 48     | 34                   | 41     | 27     | 38                                          | 56      | 41      | 44                                        | 34      | 40      | 37          | 42      | 1       | 18                | 22      | 42      | 48      | 23      | 13      | 36      | 24      | 21      | 24      | 12      | 12      | 48      | 12      | 19      | 62      |         |  |  |  |  |
| 34                 | 16     | 18     | 17                                    | 25     | 41     | 39                   | 38     | 21     | 25                                          | 39      | 15      | 41                                        | 22      | 15      | 41          | 22      | 15      | 41                | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      |  |  |  |  |
| 35                 | 21     | 48     | 21                                    | 41     | 39     | 38                   | 38     | 21     | 25                                          | 39      | 15      | 41                                        | 22      | 15      | 41          | 22      | 15      | 41                | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      | 15      | 41      | 22      |  |  |  |  |
| 43                 | 26     | 64     | 16                                    | 78     | 53     | 41                   | 37     | 61     | 23                                          | 38      | 994     | 45                                        | 78      | 37      | 45          | 78      | 37      | 45                | 78      | 37      | 45      | 78      | 37      | 45      | 78      | 37      | 45      | 78      | 37      | 45      | 78      | 37      | 45      | 78      |  |  |  |  |
| 30                 | 60     | 21     | 30                                    | 30     | 30     | 30                   | 30     | 30     | 30                                          | 30      | 30      | 30                                        | 30      | 30      | 30          | 30      | 30      | 30                | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      | 30      |         |  |  |  |  |
| 38                 | 23     | 17     | 23                                    | 23     | 23     | 23                   | 23     | 23     | 23                                          | 23      | 23      | 23                                        | 23      | 23      | 23          | 23      | 23      | 23                | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      | 23      |         |  |  |  |  |
| 24                 | 23     | 16     | 22                                    | 20     | 18     | 37                   | 22     | 24     | 16                                          | 37      | 22      | 24                                        | 16      | 37      | 22          | 24      | 16      | 37                | 22      | 24      | 16      | 37      | 22      | 24      | 16      | 37      | 22      | 24      | 16      | 37      | 22      | 24      | 16      | 37      |  |  |  |  |
| 45                 | 49     | 38     | 28                                    | 38     | 40     | 38                   | 68     | 32     | 32                                          | 43      | 32      | 86                                        | 42      | 38      | 47          | 76      | 68      | 39                | 308     | 600     | 281     | 44      | 108     | 10      | 19      | 20      | 29      | 23      | 50      | 48      | 18      | 12      | 353     | 41      |  |  |  |  |
| 38                 | 35     | 41     | 35                                    | 31     | 22     | 35                   | 28     | 31     | 22                                          | 35      | 28      | 31                                        | 22      | 35      | 28          | 31      | 22      | 35                | 28      | 31      | 22      | 35      | 28      | 31      | 22      | 35      | 28      | 31      | 22      | 35      | 28      | 31      | 22      | 35      |  |  |  |  |
| 37                 | 53     | 38     | 51                                    | 34     | 47     | 47                   | 28     | 37     | 75                                          | 153     | 53      | 53                                        | 53      | 62      | 50          | 27      | 81      | 52                | 55      | 57      | 23      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      | 31      |  |  |  |  |
| 31                 | 29     | 18     | 31                                    | 22     | 29     | 42                   | 29     | 30     | 22                                          | 28      | 28      | 28                                        | 28      | 28      | 28          | 28      | 28      | 28                | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      |         |  |  |  |  |
| 34                 | 47     | 16     | 39                                    | 29     | 34     | 42                   | 34     | 47     | 28                                          | 37      | 59      | 47                                        | 39      | 27      | 44          | 31      | 50      | 16                | 145     | 23      | 24      | 23      | 24      | 23      | 24      | 23      | 24      | 23      | 24      | 23      | 24      | 23      | 24      |         |  |  |  |  |
| 29                 | 80     | 17     | 22                                    | 15     | 23     | 41                   | 68     | 25     | 20                                          | 28      | 28      | 28                                        | 28      | 28      | 28          | 28      | 28      | 28                | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      |         |  |  |  |  |
| 49                 | 28     | 49     | 36                                    | 49     | 23     | 49                   | 36     | 49     | 23                                          | 49      | 36      | 49                                        | 23      | 49      | 36          | 49      | 23      | 49                | 36      | 49      | 23      | 49      | 36      | 49      | 23      | 49      | 36      | 49      | 23      | 49      | 36      | 49      | 23      | 49      |  |  |  |  |
| 37                 | 23     | 06     | 23                                    | 47     | 34     | 37                   | 28     | 28     | 28                                          | 28      | 28      | 28                                        | 28      | 28      | 28          | 28      | 28      | 28                | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      | 28      |         |  |  |  |  |
| 42                 | 27     | 1873   | 22                                    | 27     | 34     | 36                   | 27     | 31     | 21                                          | 27      | 31      | 27                                        | 31      | 27      | 31          | 27      | 31      | 27                | 31      | 27      | 31      | 27      | 31      | 27      | 31      | 27      | 31      | 27      | 31      | 27      | 31      | 27      | 31      | 27      |  |  |  |  |
| 141                | 21     | 34     | 23                                    | 59     | 42     | 37                   | 47     | 31     | 21                                          | 34      | 37      | 47                                        | 31      | 21      | 34          | 37      | 47      | 31                | 21      | 34      | 37      | 47      | 31      | 21      | 34      | 37      | 47      | 31      | 21      | 34      | 37      | 47      | 31      | 21      |  |  |  |  |
| 33                 | 22     | 20     | 20                                    | 27     | 20     | 28                   | 27     | 28     | 20                                          | 20      | 20      | 20                                        | 20      | 20      | 20          | 20      | 20      | 20                | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      | 20      |         |  |  |  |  |
| 22                 | 27     | 18     | 24                                    | 18     | 35     | 35                   | 26     | 22     | 27                                          | 83      | 29      | 45                                        | 27      | 35      | 24          | 29      | 38      | 42                | 50      | 32      | 13      | 26      | 14      | 33      | 30      | 52      | 16      | 20      | 39      | 13      | 424     | 37      | 13      |         |  |  |  |  |
| 57                 | 37     | 104    | 22                                    | 48     | 48     | 48                   | 71     | 48     | 68                                          | 34      | 33      | 37                                        | 37      | 37      | 37          | 37      | 37      | 37                | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      | 37      |         |  |  |  |  |
| 30                 | 33     | 33     | 20                                    | 34     | 32     | 11                   | 32     | 31     | 28                                          | 33      | 34      | 34                                        | 34      | 34      | 34          | 34      | 34      | 34                | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      | 34      |         |  |  |  |  |
| 4                  | 1      | 1      | 5                                     | 0      | 2      | 23                   | 2      | 3      | 6                                           | 1       | 0       | 0                                         | 0       | 0       | 0           | 0       | 0       | 0                 | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |         |  |  |  |  |
| 1143               | 286    | 286    | 1429                                  | 0.00   | 5.71   | 65.71                | 5.71   | 8.57   | 17.14                                       | 2.86    | 0.00    | 0.00                                      | 42.86   | 94.29   | 0.00        | 2.86    | 31.43   | 0.00              | 0.00    | 0.00    | 0.00    | 0.00    | 28.57   | 2.86    | 0.00    | 0.00    | 5.71    | 2.86    | 0.00    | 71.43   | 0.00    | 0.00    | 0.00    | 0.00    |  |  |  |  |
| 35 Users           |        |        | 1040                                  |        |        | 0% Fixed             |        |        | 12.0%                                       |         |         |                                           |         |         |             |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |  |  |  |  |
| 1100 Impositors    |        |        | Accept Count                          |        |        | FRR                  |        |        | FAR                                         |         |         |                                           |         |         |             |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |         |  |  |  |  |

2276444  
1387711  
910733  
765  
30077

Total keyphrases before challenge all profiles  
Total keyphrases before challenge against valid user  
Total keyphrases before challenge against impositor  
Average keyphrases before challenge - invalid user  
Average keyphrases before valid user challenged

|                    | Reference Profiles |        |        | Keystroke until challenge - composite |        |        |        |        | Alert Threshold = 70 |         |         |         |         | Variable digraph, trigraph and word S.D.'s |         |         |         |         | Starting alert=50 |         |         |         |         |         |         |         |         |         |         |         |    |  |  |  |  |  |
|--------------------|--------------------|--------|--------|---------------------------------------|--------|--------|--------|--------|----------------------|---------|---------|---------|---------|--------------------------------------------|---------|---------|---------|---------|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----|--|--|--|--|--|
|                    | User 1             | User 2 | User 3 | User 4                                | User 5 | User 6 | User 7 | User 8 | User 9               | User 10 | User 11 | User 12 | User 13 | User 14                                    | User 15 | User 16 | User 17 | User 19 | User 20           | User 21 | User 22 | User 24 | User 25 | User 26 | User 27 | User 28 | User 29 | User 31 | User 32 | User 34 |    |  |  |  |  |  |
| Digraph SD         | 0.6                | 0.6    | 0.6    | 0.7                                   | 0.6    | 0.7    | 0.7    | 0.7    | 0.7                  | 0.7     | 0.7     | 0.6     | 0.7     | 0.6                                        | 0.7     | 0.6     | 0.6     | 0.7     | 0.7               | 0.7     | 0.7     | 0.7     | 0.7     | 0.7     | 0.6     | 0.7     | 0.6     | 0.7     | 0.6     | 0.6     |    |  |  |  |  |  |
| Trigraph SD        | 0.5                | 0.5    | 0.5    | 0.6                                   | 0.5    | 0.6    | 0.6    | 0.6    | 0.6                  | 0.6     | 0.6     | 0.5     | 0.6     | 0.5                                        | 0.6     | 0.5     | 0.5     | 0.6     | 0.6               | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.5     | 0.6     | 0.5     | 0.6     | 0.6     | 0.5     |    |  |  |  |  |  |
| Word SD            | 0.7                | 0.5    | 0.5    | 0.6                                   | 0.6    | 0.6    | 0.6    | 0.6    | 0.6                  | 0.6     | 0.6     | 0.6     | 0.6     | 0.6                                        | 0.6     | 0.6     | 0.6     | 0.6     | 0.6               | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     | 0.6     |    |  |  |  |  |  |
| Digraph Unmatched  | No                 | No     | No     | No                                    | No     | No     | No     | No     | No                   | No      | No      | No      | No      | No                                         | No      | No      | No      | No      | No                | No      | No      | No      | No      | No      | No      | No      | No      | No      | No      | No      |    |  |  |  |  |  |
| Trigraph Unmatched | No                 | No     | No     | No                                    | No     | No     | No     | No     | No                   | No      | No      | No      | No      | No                                         | No      | No      | No      | No      | No                | No      | No      | No      | No      | No      | No      | No      | No      | No      | No      | No      |    |  |  |  |  |  |
| Threshold          | 70                 | 70     | 70     | 70                                    | 70     | 70     | 70     | 70     | 70                   | 70      | 70      | 70      | 70      | 70                                         | 70      | 70      | 70      | 70      | 70                | 70      | 70      | 70      | 70      | 70      | 70      | 70      | 70      | 70      | 70      | 70      | 70 |  |  |  |  |  |
| User 1             | 34352              | 51     | 49     | 53                                    | 73     | 44     | 50     | 16     | 102                  | 38      | 17      | 94      | 36      | 101                                        | 575     | 34      | 115     | 34      | 26                | 17      | 104     | 54      | 27      | 28      | 74      | 170     | 101     | 44      | 29      | 25      |    |  |  |  |  |  |
| User 2             | 50                 | 53306  | 27     | 46                                    | 50     | 161    | 55     | 83     | 34                   | 489     | 202     | 75      | 159     | 87                                         | 53306   | 390     | 93      | 64      | 94                | 83      | 112     | 40      | 130     | 62      | 361     | 37      | 33      | 24      | 22      | 53306   |    |  |  |  |  |  |
| User 3             | 649                | 96     | 150718 | 90                                    | 220    | 48     | 52     | 39     | 518                  | 53      | 29      | 207     | 29      | 173                                        | 519     | 78      | 137     | 39      | 39                | 20      | 210     | 70      | 62      | 30      | 98      | 1706    | 76      | 43      | 32      | 76      |    |  |  |  |  |  |
| User 4             | 72                 | 50     | 16     | 27324                                 | 39     | 34     | 37     | 16     | 47                   | 28      | 17      | 181     | 22      | 71                                         | 167     | 47      | 27      | 14      | 17                | 26      | 22      | 25      | 42      | 72      | 55      | 21      | 16      | 16      | 52      |         |    |  |  |  |  |  |
| User 5             | 181                | 39     | 117    | 25                                    | 50822  | 54     | 103    | 17     | 71                   | 239     | 35      | 238     | 22      | 1780                                       | 367     | 39      | 324     | 35      | 35                | 34      | 50822   | 67      | 30      | 27      | 505     | 110     | 106     | 35      | 26      | 37      |    |  |  |  |  |  |
| User 6             | 61                 | 37     | 20     | 31                                    | 61     | 320    | 34     | 20     | 21                   | 42      | 109     | 175     | 37      | 41                                         | 87      | 35      | 33      | 42      | 50                | 32      | 17      | 23      | 43      | 42      | 910     | 17      | 23      | 13      | 16      | 48      |    |  |  |  |  |  |
| User 7             | 744                | 57     | 102    | 52                                    | 17450  | 86     | 78579  | 86     | 78579                | 102     | 42      | 265     | 33      | 272                                        | 374     | 43      | 718     | 94      | 94                | 33      | 78579   | 83      | 43      | 46      | 78579   | 272     | 223     | 295     | 297     | 39      |    |  |  |  |  |  |
| User 8             | 45                 | 30     | 25     | 24                                    | 59     | 51     | 58     | 71     | 29                   | 47      | 30      | 44      | 47      | 45                                         | 280     | 40      | 50      | 34      | 47                | 29      | 50102   | 35      | 24      | 36      | 75      | 35      | 60      | 22      | 26      | 63      |    |  |  |  |  |  |
| User 9             | 44                 | 21     | 31     | 35                                    | 39     | 35     | 41     | 12     | 37618                | 34      | 32      | 40      | 16      | 69                                         | 77      | 29      | 41      | 33      | 19                | 21      | 44      | 102     | 23      | 29      | 58      | 54      | 40      | 47      | 19      | 31      |    |  |  |  |  |  |
| User 10            | 48                 | 69     | 12     | 53                                    | 32     | 38     | 29     | 28     | 52                   | 70337   | 39      | 79      | 27      | 86                                         | 194     | 33      | 16      | 14      | 16                | 18      | 35      | 22      | 101     | 34      | 345     | 16      | 16      | 11      | 12      | 53      |    |  |  |  |  |  |
| User 11            | 79                 | 254    | 19     | 36                                    | 67     | 64     | 51     | 70     | 38                   | 522     | 1187    | 59      | 64      | 447                                        | 345     | 59      | 72      | 49      | 64                | 54      | 720     | 53      | 38      | 42      | 94      | 34      | 40      | 40      | 35      | 317     |    |  |  |  |  |  |
| User 12            | 142                | 133    | 61     | 137                                   | 63     | 72     | 49     | 39     | 71                   | 121     | 56      | 20216   | 44      | 122                                        | 518     | 133     | 50      | 37      | 41                | 37      | 72      | 39      | 218     | 71      | 119     | 87      | 38      | 29      | 27      | 133     |    |  |  |  |  |  |
| User 13            | 114                | 87     | 16     | 61                                    | 82     | 96     | 41     | 18     | 52                   | 92      | 28      | 138     | 1043    | 92                                         | 216     | 27      | 87      | 18      | 22                | 22      | 215     | 25      | 124     | 46      | 49      | 16      | 24      | 12      | 19      | 18      |    |  |  |  |  |  |
| User 14            | 137                | 27     | 54     | 48                                    | 196    | 53     | 87     | 25     | 100                  | 46      | 381     | 91      | 44      | 33639                                      | 115     | 95      | 39      | 49      | 45                | 48      | 578     | 48      | 77      | 39      | 444     | 50      | 171     | 41      | 35      | 96      |    |  |  |  |  |  |
| User 15            | 137                | 21     | 97     | 23                                    | 142    | 93     | 104    | 53     | 65                   | 15951   | 29      | 38      | 78      | 473                                        | 15951   | 36      | 36      | 97      | 59                | 59      | 15951   | 56      | 21      | 27      | 489     | 63      | 142     | 53      | 54      | 50      |    |  |  |  |  |  |
| User 16            | 56                 | 42839  | 37     | 69                                    | 100    | 89     | 50     | 41     | 44                   | 42839   | 994     | 100     | 79      | 566                                        | 42839   | 42839   | 53      | 29      | 39                | 62      | 1059    | 48      | 104     | 64      | 983     | 59      | 58      | 26      | 28      | 42839   |    |  |  |  |  |  |
| User 17            | 255                | 44     | 47     | 53                                    | 51     | 39     | 55     | 17     | 1599                 | 23      | 23      | 83      | 33      | 105                                        | 175     | 44      | 105543  | 17      | 29                | 37      | 58      | 68      | 48      | 41      | 58      | 232     | 49      | 44      | 17      | 51      |    |  |  |  |  |  |
| User 19            | 311                | 94     | 94     | 52                                    | 87     | 72     | 69     | 49     | 134                  | 53      | 43      | 82      | 86      | 153                                        | 330     | 102     | 220     | 11273   | 43                | 48      | 103876  | 97      | 44      | 38      | 533     | 109     | 350     | 96      | 113     | 120     |    |  |  |  |  |  |
| User 20            | 71                 | 89     | 53     | 63                                    | 57     | 46     | 53     | 25     | 57                   | 78597   | 7819    | 113     | 25      | 78597                                      | 703     | 51      | 28      | 41      | 78597             | 257     | 78597   | 38      | 30      | 41      | 78597   | 52      | 78      | 31      | 38      | 126     |    |  |  |  |  |  |
| User 21            | 111                | 80626  | 12     | 86                                    | 27     | 98     | 44     | 14     | 47                   | 148     | 114     | 99      | 19      | 290                                        | 328     | 330     | 15      | 39      | 308               | 80626   | 115     | 32      | 47      | 61      | 114     | 30      | 74      | 18      | 12      | 167     |    |  |  |  |  |  |
| User 22            | 399                | 69     | 180    | 79                                    | 175    | 69     | 71     | 25     | 256                  | 106     | 155     | 119     | 55      | 262                                        | 735     | 57      | 147     | 55      | 57                | 28      | 117365  | 152     | 58      | 53      | 528     | 201     | 349     | 34      | 55      | 72      |    |  |  |  |  |  |
| User 24            | 2118               | 39     | 25     | 23                                    | 283    | 50     | 68     | 24     | 281                  | 23      | 28      | 59      | 49      | 72                                         | 111     | 33      | 281     | 26      | 24                | 23      | 135     | 201260  | 21      | 33      | 93      | 27      | 284     | 192     | 149     | 22      |    |  |  |  |  |  |
| User 25            | 87                 | 129    | 16     | 232                                   | 41     | 47     | 44     | 21     | 31                   | 241     | 47      | 273     | 27      | 85                                         | 79      | 80      | 31      | 23      | 36                | 44      | 40      | 27      | 38944   | 50      | 64      | 15      | 32      | 9       | 7       | 53      |    |  |  |  |  |  |
| User 26            | 73                 | 48469  | 11     | 211                                   | 44     | 144    | 31     | 14     | 53                   | 53      | 53      | 48469   | 142     | 121                                        | 173     | 424     | 26      | 22      | 44                | 149     | 37      | 21      | 48469   | 48469   | 71      | 21      | 22      | 14      | 14      | 48469   |    |  |  |  |  |  |
| User 27            | 65                 | 137    | 17     | 44                                    | 56     | 82     | 78     | 58     | 107                  | 32      | 26      | 269     | 93      | 609                                        | 586     | 266     | 40      | 60      | 47                | 44      | 33068   | 27      | 98      | 53      | 33068   | 39      | 60      | 10      | 18      | 269     |    |  |  |  |  |  |
| User 28            | 505                | 30     | 354    | 79                                    | 169    | 66     | 49     | 49     | 192                  | 34      | 21      | 81      | 27      | 61                                         | 305     | 54      | 590     | 25      | 32                | 23      | 70217   | 148     | 37      | 41      | 157     | 70217   | 179     | 53      | 76      | 29      |    |  |  |  |  |  |
| User 29            | 474                | 34     | 30     | 52                                    | 72     | 52     | 52     | 23     | 75                   | 52      | 38      | 66      | 20      | 68                                         | 1448    | 44      | 309     | 43      | 23                | 19      | 88059   | 74      | 49      | 35      | 51      | 3013    | 88059   | 31      | 25      | 35      |    |  |  |  |  |  |
| User 31            | 310823             | 37     | 310823 | 38                                    | 38     | 54     | 153    | 26     | 310823               | 14      | 17      | 59      | 22      | 284                                        | 213     | 38      | 310823  | 33      | 38                | 27      | 310823  | 310823  | 37      | 37      | 73      | 310823  | 310823  | 310823  | 409     | 57      |    |  |  |  |  |  |
| User 32            | 1373               | 69     | 111    | 75                                    | 131    | 59     | 73     | 37     | 86                   | 43      | 21      | 141     | 37      | 114                                        | 131     | 70      | 61      | 53      | 31                | 21      | 128     | 371     | 64      | 37      | 503     | 3113    | 95      | 30      | 353667  | 38      |    |  |  |  |  |  |
| User 34            | 48                 | 73     | 22     | 123                                   | 24     | 77     | 34     | 18     | 38                   | 64      | 63      | 396     | 45      | 73                                         | 2490    | 73      | 209     | 22      | 30                | 34      | 62      | 34      | 101     | 42      | 65      | 26      | 48      | 20      | 24      | 124409  |    |  |  |  |  |  |
| total              | 28                 | 28     | 28     | 29                                    | 29     | 29     | 29     | 27     | 27                   | 28      | 28      | 28      | 29      | 28                                         | 29      | 27      | 29      | 28      | 29                | 29      | 28      | 28      | 28      | 29      | 27      | 28      | 29      | 29      | 29      | 29      |    |  |  |  |  |  |
| FAR                | 1                  | 1      | 1      | 0                                     | 0      | 0      | 0      | 2      | 2                    | 1       | 1       | 1       | 0       | 1                                          | 2       | 0       | 1       | 0       | 0                 | 0       | 1       | 1       | 1       | 1       | 0       | 2       | 1       | 1       | 0       | 0       |    |  |  |  |  |  |
| 30 Users           | 3.33               | 3.33   | 3.33   | 0.00                                  | 0.00   | 0.00   | 0.00   | 6.67   | 6.67                 | 3.33    | 3.33    | 3.33    | 0.00    | 3.33                                       | 6.67    | 0.00    | 3.33    | 0.00    | 0.00              | 0.00    | 3.33    | 3.33    | 3.33    | 0.00    | 6.67    | 3.33    | 3.33    | 0.00    | 0.00    | 0.00    |    |  |  |  |  |  |
| 870 impostors      |                    |        |        |                                       |        |        |        |        |                      |         |         |         |         |                                            |         |         |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |    |  |  |  |  |  |
| Accept Count       | 849                |        |        |                                       |        |        |        |        |                      |         |         |         |         |                                            |         |         |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |    |  |  |  |  |  |
| FRR                | 0% Fixed           |        |        |                                       |        |        |        |        |                      |         |         |         |         |                                            |         |         |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |    |  |  |  |  |  |
| FAR                | 2.4%               |        |        |                                       |        |        |        |        |                      |         |         |         |         |                                            |         |         |         |         |                   |         |         |         |         |         |         |         |         |         |         |         |    |  |  |  |  |  |

# **Appendix D**

## ***Published Papers***

## Published Papers

The list below presents papers written and published during the PhD work programme. Those highlighted with a '\*' are not included in this appendix but are available from the Network Research Group web site (<http://www.network-research-group.org>).

1. "A Long-Term Trial Of Keystroke Profiling Using Digraph, Trigraph And Keyword Latencies", Dowland P.S. and Furnell S.M., Accepted for publication in the *Proceedings of the IFIP SEC 2004 Conference*, Toulouse, France, August 2004
- \* 2. "A Correlation Framework for Continuous User Authentication Using Data Mining", Singh H., Furnell S.M., Dowland P.S., Lines B. and Kaur S., Accepted for publication in the *Proceedings of the Fourth International Network Conference (INC 2004 )*, Plymouth, UK, July 2004
- \* 3. "A long-term trial of alternative user authentication technologies", Furnell S.M., Papadopoulos I. and Dowland P.S., Accepted for publication in *Information Management and Computer Security*, 2004



- \* 4. "Improving Security Awareness And Training Through Computer-Based Training", Furnell S.M., Warren A. and Dowland P.S., *Proceedings of the WISE Conference*, Monterey, USA, July, pp287-301, 2003
- \* 5. "Assessing IT Security Culture: System Administrator and End-User", Finch J., Furnell S.M. and Dowland P.S., *Proceedings of ISOneWorld Conference 2003*, Las Vegas, USA, April 23-25, 2003
- \* 6. "A prototype tool for information security awareness and training", Furnell S.M., Gennatou M. and Dowland P.S., *International Journal of Logisitics Information Management*, vol. 15, no. 5, pp352-357, 2002
- \* 7. "Critical awareness – The problem of monitoring security vulnerabilities", Furnell S.M., Alayed A., Barlow I. and Dowland P.S., *Proceedings of European Conference on Information Warfare and Security*, 8-9 July 2002, Brunel, UK, pp85-92 2002
- \* 8. "An experimental comparison of secret-based user authentication technologies", Irakleous I., Furnell S.M., Dowland P.S. and Papadaki M., *Information Management & Computer Security*, vol. 10, no. 3, pp100-108, 2002

9. "Keystroke Analysis as a Method of Advanced User Authentication and Response", Dowland P.S., Furnell S.M. and Papadaki M., *Proceedings of IFIP/SEC 2002 - 17th International Conference on Information Security*, Cairo, Egypt, 7-9 May, pp215-226, 2002
10. "A Preliminary Investigation of User Authentication Using Continuous Keystroke Analysis", Dowland P.S., Singh H. and Furnell S.M., *Proceedings of the IFIP 8th Annual Working Conference on Information Security Management & Small Systems Security*, Las Vegas, 27-28 September, 2001
- \* 11. "Security analysers: Administrator Assistants or Hacker Helpers?", Furnell S.M., Chiliarchaki P. and Dowland P.S., *Information Management and Computer Security*, vol. 9, no.2, pp93-101, 2001
- \* 12. "Investigating and Evaluating Behavioural Profiling and Intrusion Detection Using Data Mining", Singh H., Furnell S.M., Lines B. and Dowland P.S., *Proceedings of International Workshop on Mathematical Methods, Models and Architectures for Computer Networks Security*, St. Petersburg, Russia, 21-23 May, 2001
- \* 13. "A Generic Taxonomy for Intrusion Specification and Response", Furnell S.M., Magklaras G.B., Papadaki M. and Dowland P.S., *Proceedings of Euromedia 2001*, Valencia, Spain, 18-20 April, 2001

- \* 14. "Promoting security awareness and training within small organisations",  
Furnell S.M., Gennatou M. and Dowland P.S., *Proceedings of the First Australian Information Security Management (AISM) Workshop*,  
Geelong, Australia, 7 November, 2000
- 15. "Authentication and Supervision: A survey of user attitudes", Furnell  
S.M., Dowland P.S., Illingworth H.M. and Reynolds P.L., *Computers &  
Security*, vol. 19, no. 6, pp529-539, 2000
- 16. "A conceptual intrusion monitoring architecture and thoughts on  
practical implementation", Dowland P.S. and Furnell S.M., *Proceedings  
of the World Computer Congress 2000*, 21-25 August, 2000
- 17. "Enhancing Operating System Authentication Techniques", Dowland  
P.S. and Furnell S.M., *Proceedings of the Second International Network  
Conference (INC 2000)*, Plymouth, UK, pp253-261, 3-6 July, 2000
- 18. "A conceptual architecture for real-time intrusion monitoring", Furnell  
S.M. and Dowland P.S., *Information Management & Computer Security*,  
vol. 8, no. 2, pp65-74, 2000
- \* 19. "Developing tools to support online distance learning", Furnell S.M.,  
Evans M.P. and Dowland P.S., *Proceedings of EUROMEDIA 2000*,  
Antwerp, Belgium, 8-10 May, 2000

- \* 20. "Computer Crime and Abuse: A Survey of Public Attitudes and Awareness", Dowland P.S., Furnell S.M., Illingworth H.M. and Reynolds P.L., *Computers & Security*, vol. 18, no. 8, pp715-726, 1999
  
- \* 21. "Dissecting the 'Hacker Manifesto'", Furnell S.M., Dowland P.S. and Sanders P., *Information Management and Computer Security*, vol.7, no.2 pp69-75, 1999

# **A Long-term Trial of Keystroke Profiling using Digraph, Trigraph and Keyword Latencies**

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**Abstract:** A number of previous studies have investigated the use of keystroke analysis as a means of authenticating users' identities at the point of initial login. By contrast, relatively little research has focused upon the potential of applying the technique for identity verification during the logged-in session. Previous work by the authors has determined that keystroke analysis is a viable metric for continuous monitoring, provided that sufficient data is captured to create a reliable profile. This paper presents a series of results from a three-month trial in which profiles were created using digraph, trigraph and keyword-based keystroke latencies. The profiles were based upon a total of over 5 million keystroke samples, collected from 35 participants. The results demonstrate that the techniques offer significant promise as a means of non-intrusive identity verification during keyboard-related activities, with an optimum false acceptance rate of 4.9% being observed at a rate of 0% false rejection.

**Key words:** Authentication, Misuse Detection

## **1. INTRODUCTION**

Over the last twenty years, the concept of keystroke analysis has been the focus of considerable research as a means of user authentication. The potential for profiling of keypresses was first identified by Gaines et al (1980). Since then, a number of research projects have been conducted to evaluate different methods of data gathering (using a range of operating systems and considering a variety of metrics) and post-processing techniques (ranging from purely statistical to AI/neural network approaches).

To date, however, virtually all published studies have focussed upon looking at the application of static strings, such as username and password pairs using the inter-keystroke digraph latency timing method. From the earliest studies in 1980 (Card et al & Gaines et al), the focus has been on the analysis of digraph latencies. Later studies, such as those by Joyce & Gupta (1990) and Mahar et al (1995) further enhanced the work, identifying additional statistical analysis methods that provided more reliable results.

In Legget et al. (1991), the concept of dynamic keystroke analysis was first proposed, with the introduction of a reference profile that could be used to monitor a live user session. Brown and Rogers (1993) also explored the idea of dynamic analysis, presenting preliminary results.

The authors' previous research (Dowland et al., 2002) described an experiment evaluating keystroke analysis based on inter-keystroke digraph latencies under Windows. This earlier trial concentrated upon the capture and subsequent analysis of digraph latencies using inter-keystroke timings. The trial results demonstrated the viability of this method, but suggested that, to be a reliable authentication measure, user profiles would need to be based upon much larger sample sizes. The previous trial was also based on a limited number of users in order to quickly evaluate the viability of the technique.

This paper presents the results of a long-term trial that was aimed at evaluating a range of techniques using a larger number of participants. This trial captured and evaluated trigraph and keyword latencies, in addition to digraph timings, under the Windows operating system. The paper begins by introducing the technical aspects of the trial conducted over a three month period before considering the statistical approach taken with the data analysis stage. The results are presented and discussed, leading to some overall conclusions, and proposals for future work.

## **2. CAPTURING KEYSTROKE DATA IN WINDOWS**

While keystroke analysis has been investigated (and hence implemented) in previous studies, a GUI environment (e.g. Microsoft Windows) introduces new challenges. In previous published studies, the user has been required to type and interact with a specific application (typing either pre-defined or free-form text). While this approach makes the development of the keystroke monitoring software simple, and maintains the consistency of the

test environment, it is not representative of normal typing behaviour as the user becomes focussed upon the task of typing, rather than focussed upon a task that *involves* typing. If the aim is to produce static keystroke analysis for occasional authentication judgements (e.g. supplementing login authentication) then this approach will work well. However, to implement continuous supervision using dynamic keystroke analysis it is necessary to monitor the users' normal behaviour when interacting with their normal applications and operating system environment. Even providing a simulation of these environments may not be sufficient to obtain valid sample data upon which to base a profile.

In order to address this problem, software was developed that would transparently monitor and log all typing activity. The system was designed to allow keystroke data to be collected under the Microsoft Windows XP environment (although the technique is equally applicable in all Windows operating systems). In order to collect the required data, it was necessary to implement a mechanism for acquiring user typing patterns across all applications running within a users' active session. This is important as the experiment was designed to create a profile for each user based upon their typical typing patterns when using their computer (not constrained to a specific application or task). The implementation of the keylogger utilised several key features of the Windows operating system and the underlying chains of messages on which the operating system is built (these are briefly discussed in the following section). The authors have not investigated the applicability of these techniques under other operating systems but it is likely that the same system could be developed under other systems providing access is given to the keypress events at an appropriate level.

Figure 1 illustrates the software architecture used to capture and log keystroke activity under Windows. As keys are pressed, messages are generated by Windows for both key up and down events. These messages are captured through the use of a hook function that redirects messages to a nominated program. The messages are passed from the hook (implemented as a system-wide DLL written in C) to the keylogger (implemented in Visual Basic and deployed as a system tray application). The keylogger functioned completely transparently to the user, requiring no user action to start or stop the logging process. The application was automatically started when the operating system (O/S) booted (run from the Startup program group on the start menu) and shut down automatically when the O/S closed. Gathered data was automatically saved after every 500 digraphs pairs and when the application was closed. To reassure users, an option was included to

suspend logging of keystrokes. This was included due to concerns expressed by some users about monitoring of specific inputs – e.g. the typing of on-line banking login details.

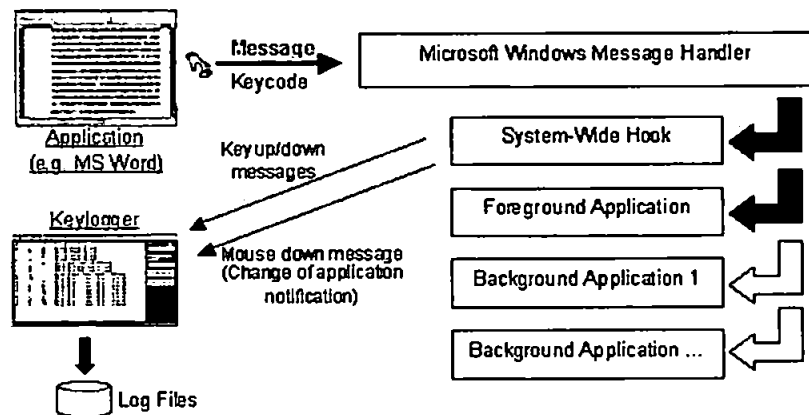


Figure 1. Implementation of keylogger

For each digraph pair logged, the application stored five items of information (Table 1) – these being written to an Access database after every 500 digraphs. This process was also repeated for each trigraph and keyword latency (i.e. trigraphs were stored as three consecutive characters and keywords as a string).

Table 1. Keylogger attributes logged per digraph

| Item                 | Data types                                                                                                                                 |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| AutoID               | Auto-incrementing record number. This is used to maintain the order of the keystrokes typed as the timestamp is only accurate to 1 second. |
| Left character (C1)  | ASCII code representing character                                                                                                          |
| Right character (C2) | ASCII code representing character                                                                                                          |
| Latency              | Integer representing inter-keystroke latency in milliseconds                                                                               |
| Application          | String containing the window title from the foreground application.                                                                        |
| Timestamp            | A timestamp is added to every keystroke logged for later use.                                                                              |

While digraph and trigraph logging were based upon all keystrokes entered, keyword logging was based on a look up list. The top 200 commonly occurring words in the English language were monitored, and as each word was entered, its latency was recorded.

### 3. EXPERIMENTAL PROCEDURE

For this experiment a total of 35 users were profiled over a period of



three months. Unfortunately several users disabled the keylogger when entering sensitive information and consequently forgot to re-enable it. Despite this, the key-logging trial collected considerable volumes of data with nearly six million samples collected across digraphs, trigraphs and keywords (Table 2).

*Table 2. User profile results*

| User    | Mean Digraph Latency (ms) | Typing Skill Classification | Digraphs  | Trigraphs | Words   |
|---------|---------------------------|-----------------------------|-----------|-----------|---------|
| User 1  | 91                        | Best                        | 34352     | 23352     | 1403    |
| User 2  | 156                       | Average (skilled)           | 53306     | 36912     | 2599    |
| User 3  | 99                        | Best                        | 156718    | 107107    | 6154    |
| User 4  | 251                       | Average (non-skilled)       | 27324     | 18688     | 1310    |
| User 5  | 112                       | Good                        | 50822     | 36713     | 1465    |
| User 6  | 154                       | Average (skilled)           | 50167     | 34484     | 1885    |
| User 7  | 106                       | Good                        | 78579     | 54959     | 4349    |
| User 8  | 130                       | Good                        | 50102     | 35102     | 2932    |
| User 9  | 97                        | Best                        | 37618     | 24755     | 1741    |
| User 10 | 145                       | Average (skilled)           | 70337     | 48942     | 4643    |
| User 11 | 147                       | Average (skilled)           | 227660    | 145846    | 10617   |
| User 12 | 102                       | Good                        | 20216     | 14142     | 1032    |
| User 13 | 157                       | Average (skilled)           | 65312     | 43015     | 1730    |
| User 14 | 141                       | Average (skilled)           | 33639     | 23090     | 1784    |
| User 15 | 139                       | Good                        | 15951     | 11159     | 1068    |
| User 16 | 150                       | Average (skilled)           | 42839     | 30299     | 2037    |
| User 17 | 106                       | Good                        | 105543    | 68068     | 3173    |
| User 18 | 177                       | Average (skilled)           | 89730     | 59292     | 3121    |
| User 19 | 117                       | Good                        | 103876    | 71635     | 4617    |
| User 20 | 121                       | Good                        | 78597     | 53495     | 4479    |
| User 21 | 141                       | Average (skilled)           | 80626     | 55881     | 2807    |
| User 22 | 110                       | Good                        | 117365    | 79534     | 6557    |
| User 23 | 131                       | Good                        | 118805    | 77013     | 5682    |
| User 24 | 89                        | Best                        | 201260    | 131954    | 8517    |
| User 25 | 203                       | Average (skilled)           | 38944     | 26655     | 2266    |
| User 26 | 192                       | Average (skilled)           | 48469     | 33907     | 2555    |
| User 27 | 125                       | Good                        | 33068     | 23115     | 1679    |
| User 28 | 91                        | Best                        | 70217     | 47033     | 2128    |
| User 29 | 104                       | Good                        | 88059     | 55707     | 3815    |
| User 30 | 202                       | Average (skilled)           | 40741     | 28789     | 1007    |
| User 31 | 86                        | Best                        | 310823    | 211419    | 19726   |
| User 32 | 93                        | Best                        | 353867    | 237274    | 18056   |
| User 33 | 144                       | Average (skilled)           | 276669    | 183455    | 6057    |
| User 34 | 143                       | Average (skilled)           | 124409    | 87079     | 953     |
| User 35 | 130                       | Good                        | 140044    | 85413     | 6240    |
| Totals  |                           |                             | 3,436,054 | 2,305,283 | 150,184 |

Before considering the data from each user, the typing skill for each participant was evaluated based on the categorisations proposed by Card et al. (1980) where typists are broadly categorised into one of six categories. The results are presented in Table 2 together with the quantity of samples for each user (shown separately for digraph, trigraph and keywords). The results are weighted towards typists with above average skills due to the nature of the test subjects (i.e. all subjects were regular computer users who spent prolonged periods typing). This was considered acceptable as the likely use for a fully implemented system would be in environments with semi-skilled users (i.e. relatively few unskilled/poor typists).

#### **4. STATISTICAL ANALYSIS**

To eliminate extreme short/long digraph latencies that may adversely affect the distribution of digraph times, any digraph pair whose latency fell outside a nominal range was excluded from the log files. For the purpose of this experiment the range was restricted to times above 10ms and below 750ms. In an earlier trial the range was restricted to 40ms – 750ms, with these thresholds based on previous work conducted by Furnell (1995), and were designed to eliminate samples where two keys may have been accidentally struck together (thus, producing an infeasibly small latency) or, where the user may have made a pause in their typing and thus introduced an unnaturally large inter-keystroke latency. Unfortunately, the low pass filter was responsible for substantial quantities of data being removed from the user profiles and, as such, was reduced to 10ms for the purposes of this trial. If a digraph was removed due to the filtering, this also reset the trigraph and keyword logging so no further thresholds were needed for these two measures.

Following the initial filtering, the experimental data for each user was processed off-line to calculate the mean and standard deviation values for each unique digraph, trigraph or keyword. In the event that any profiled sample had a standard deviation greater than its mean value, the samples were sorted and the top/bottom 10% was then removed, followed by subsequent re-calculation of the mean and standard deviation values. The reason for this additional step was to remove samples where the latencies would have an adverse affect on the standard deviation (i.e. the distribution of samples was tightened).

Once all the user profiles were calculated, another application (the data comparator) was used to generate tables of results for each of the methods.

The data comparator (Figure 2) was based on the original analyser developed in the previous trial (Dowland et al., 2002). A small number of additional features were introduced to the comparator to cater for the inclusion of trigraphs and keyword profiles.

Digraph

User 1  
User 2  
User 3  
User 4  
User 5  
User 6  
User 7  
User 8  
User 9  
User 10  
User 11  
User 12

Process Profile Data

S.Dev's

☒ Increase Alert on Unmatched

☒ Digraph ☐ Trigraph ☐ Word

Start Time 19/02/2004 16:36:53

End Time

Profile MDB  
C:\Documents and Settings\Administrator\My Documents\WorkPackage5a\Data pr ...

Data directory - end '\'  
C:\Documents and Settings\Administrator\My Documents\WorkPackage5a\Data processin\

|                       | Digraph | Trigraph | Word |
|-----------------------|---------|----------|------|
| Profiled Digraphs     | 3       |          |      |
| Matched               | 0       |          |      |
| Unmatched             | 2555    |          |      |
| Consecutive Unmatched | 2555    |          |      |
| High Accepted         | 0       |          |      |
| High Rejected         | 0       |          |      |
| Highest Alert Level   | 2605    |          |      |

Figure 2. Data comparator (running)

In the previous trial, when a digraph was processed that did not exist in the reference profile, the alert level remained static (simply increasing the count of unmatched digraphs). This trial considered the role of unmatched samples as they are a potential indicator of impostor activity. I.e. if a user types a specific sample infrequently (to the extent that there is insufficient data on which to base a profile), it is reasonable to assume that these occurrences are un-representative of that user's normal typing behaviour. By default, in this trial, an unmatched sample increased the alert level by one, whilst a matched accepted/rejected sample varied the alert level by two accordingly. This behaviour can be adjusted by selecting the checkbox in

the comparator – once unchecked; the alert level was not affected by unmatched samples.

Before starting the full profile comparisons a trial comparison was conducted based on a random selection of five users in order to determine the optimum settings for the deviation threshold. In the previous study the deviation settings were chosen from a range of 0.5, 1.0, 1.5 and 2.0 standard deviations with the best results obtained at 0.5. In order to determine an optimum setting, profile comparisons were made between 0.5 and 1.0 standard deviations (values below 0.5 had already been assessed in earlier trials). For the randomly selected users the best results were obtained at 0.7 with an increase in alert level above and below this threshold. As such, the later comparisons were performed with standard deviations settings of 0.6, 0.7 and 0.8. The permitted deviation was determined by the slider control that selects the number of standard deviations from the mean.

$$\text{digraph mean} \pm (\text{digraph standard deviation} * \text{permitted deviation})$$

Once the profile comparison was started each users' reference profile was loaded and then compared against the raw keylogger data files for all 35 users. This resulted in a table of 35 sets of statistics for each user. This process was repeated for trigraphs and keywords with three different profile deviation settings (0.6, 0.7 and 0.8 standard deviations from the mean). NB a setting of 0.5 standard deviations was introduced to the trigraph comparisons due to poor performance at 0.6 and 0.7 and unmatched alert increases were optionally applied to digraphs and trigraphs (hence doubling the number of comparisons for these metrics). With an average of nearly 100,000 samples per data file, each data comparison took approximately two hours with a total of 17 comparisons conducted – six for digraph, eight for trigraph and three for keywords (see Table 3).

*Table 3. Profile comparison settings*

| Metric    | Standard Deviations (S.D.)                                                         |
|-----------|------------------------------------------------------------------------------------|
| Digraphs  | 0.6, 0.7, 0.8 S.D.                                                                 |
| Trigraphs | 0.5, 0.6, 0.7, 0.8 S.D.<br><i>0.5 added due to poor performance at 0.6 and 0.7</i> |
| Keyword   | 0.6, 0.7, 0.8 S.D.                                                                 |

Once the profile comparison was completed, the results were exported and a number of functions were used to derive 2-dimensional tables of data from the raw results from the comparator from which the FAR/FRR figures could be derived.

Following the basic analysis described in this section, a further modification was made to the comparator to determine how many keystrokes were needed before either the valid user was challenged or an impostor detected. The threshold for this challenge was based upon the best performance thresholds from the earlier trials and was initially set at an alert level of 70. The results from this trial using the digraph keylogger files at a threshold of 0.7 standard deviations is presented in Table 4. The results from this trial were somewhat variable, while some users had good results (e.g. user 7, 10 and 26), most user profiles had only moderately successful results. If we consider user 2, while 29/34 (85%) impostors were challenged in less than 100 digraphs, user 16 (when acting as an impostor against user 2's reference profile) was able to type over 40,000 digraphs before being challenged.

The results in Table 4 can also be considered in terms of the average number of keystrokes required before a challenge is issued. The results show that an average of 6,390 digraphs were accepted before an impostor was challenged compared with an average of 68,755 digraphs before the valid user was challenged. While these results seem to provide the appropriate differentiation between impostor and valid user, giving an impostor the opportunity to type over 6,000 digraphs presents a major security risk.

Table 4. Number of keypresses before a challenge

[illegible]

For this trial the False Rejection Rate (FRR) was fixed at 0% (i.e. the valid user would not be rejected by the system). The False Acceptance Rates (FAR's) were then calculated for each user at the deviation thresholds specified in Table 3, and are shown in Table 5.

Table 5. Results from single-metric measures

| Standard Deviation | Digraph FAR |      |      |      |      |      | Triumph FAR |      |      |      |      |      | Keyword FAR |      |      |      |      |      |
|--------------------|-------------|------|------|------|------|------|-------------|------|------|------|------|------|-------------|------|------|------|------|------|
|                    | 0.6         |      |      | 0.7  |      |      | 0.8         |      |      | 0.5  |      |      | 0.6         |      |      | 0.7  |      |      |
|                    | N           | Y    | N    | Y    | N    | Y    | N           | Y    | N    | Y    | N    | Y    | N           | Y    | N    | Y    | N    | Y    |
| Unmatched Alert    | 2.9         | 2.9  | 2.9  | 8.6  | 2.9  | 8.6  | 8.6         | 8.6  | 17.1 | 8.6  | 8.6  | 8.6  | 25.7        | 8.6  | 31.4 | 97.1 | 97.1 | 91.4 |
| User 1             | 2.9         | 2.9  | 2.9  | 5.7  | 2.9  | 11.4 | 34.3        | 0.0  | 34.3 | 34.3 | 34.3 | 34.3 | 5.7         | 31.4 | 8.6  | 2.9  | 2.9  | 5.7  |
| User 2             | 0.0         | 0.0  | 0.0  | 2.9  | 5.7  | 5.7  | 11.4        | 74.3 | 5.7  | 62.9 | 62.9 | 54.3 | 20.0        | 40.0 | 25.7 | 0.0  | 8.6  | 20.0 |
| User 3             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 2.9         | 5.7  | 5.7  | 5.7  | 5.7  | 5.7  | 5.7         | 5.7  | 5.7  | 5.7  | 0.0  | 0.0  |
| User 4             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 5             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 6             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 7             | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 8             | 11.4        | 5.7  | 2.9  | 5.7  | 2.9  | 40.0 | 28.6        | 17.1 | 28.6 | 28.6 | 25.7 | 28.6 | 25.7        | 37.1 | 0.0  | 0.0  | 2.9  | 8.6  |
| User 9             | 2.9         | 2.9  | 2.9  | 0.0  | 0.0  | 0.0  | 14.3        | 17.1 | 5.7  | 17.1 | 17.1 | 17.1 | 11.4        | 14.3 | 20.0 | 22.9 | 25.7 | 34.3 |
| User 10            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 11            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 12            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 13            | 8.6         | 11.4 | 5.7  | 11.4 | 14.3 | 11.4 | 40.0        | 2.9  | 40.0 | 40.0 | 37.1 | 11.4 | 37.1        | 11.4 | 8.6  | 8.6  | 11.4 | 14.3 |
| User 14            | 2.9         | 2.9  | 2.9  | 8.6  | 0.0  | 34.3 | 8.6         | 8.6  | 8.6  | 8.6  | 8.6  | 8.6  | 22.9        | 5.7  | 28.6 | 0.0  | 2.9  | 5.7  |
| User 15            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 16            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 17            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 18            | 8.6         | 11.4 | 17.1 | 8.6  | 17.1 | 25.7 | 48.6        | 17.1 | 42.9 | 42.9 | 40.0 | 0.0  | 37.1        | 5.7  | 28.6 | 8.6  | 11.4 | 17.1 |
| User 19            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 20            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 21            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 22            | 2.9         | 8.6  | 5.7  | 8.6  | 8.6  | 25.7 | 65.7        | 0.0  | 57.1 | 57.1 | 45.7 | 5.7  | 31.4        | 17.1 | 0.0  | 5.7  | 5.7  | 11.4 |
| User 23            | 68.6        | 54.3 | 51.4 | 62.9 | 60.0 | 80.0 | 71.4        | 45.7 | 71.4 | 68.6 | 34.3 | 68.6 | 45.7        | 37.1 | 37.1 | 45.7 | 45.7 | 45.7 |
| User 24            | 2.9         | 0.0  | 2.9  | 5.7  | 5.7  | 8.6  | 62.9        | 2.9  | 54.3 | 54.3 | 25.7 | 14.3 | 28.6        | 0.0  | 2.9  | 8.6  | 14.3 | 14.3 |
| User 25            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 26            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 27            | 2.9         | 2.9  | 2.9  | 17.1 | 2.9  | 48.6 | 11.4        | 11.4 | 11.4 | 11.4 | 11.4 | 28.6 | 11.4        | 45.7 | 8.6  | 2.9  | 5.7  | 5.7  |
| User 28            | 2.9         | 2.9  | 2.9  | 5.7  | 2.9  | 17.1 | 42.9        | 8.6  | 42.9 | 42.9 | 42.9 | 17.1 | 42.9        | 14.3 | 8.6  | 17.1 | 28.6 | 37.1 |
| User 29            | 5.7         | 5.7  | 2.9  | 22.9 | 20.0 | 48.6 | 48.6        | 11.4 | 42.9 | 42.9 | 42.9 | 20.0 | 42.9        | 22.9 | 11.4 | 8.6  | 14.3 | 31.4 |
| User 30            | 14.3        | 8.6  | 14.3 | 14.3 | 11.4 | 20.0 | 22.9        | 0.0  | 20.0 | 20.0 | 20.0 | 22.9 | 22.9        | 20.0 | 37.1 | 45.7 | 28.6 | 8.6  |
| User 31            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 32            | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0         | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| User 33            | 17.1        | 14.3 | 17.1 | 14.3 | 22.9 | 28.6 | 88.6        | 77.1 | 82.9 | 82.9 | 65.7 | 54.3 | 57.1        | 71.4 | 80.0 | 68.6 | 20.0 | 28.6 |
| User 34            | 5.7         | 2.9  | 11.4 | 14.3 | 14.3 | 14.3 | 60.0        | 0.0  | 48.6 | 48.6 | 42.9 | 0.0  | 37.1        | 2.9  | 97.1 | 97.1 | 97.1 | 97.1 |
| User 35            | 22.9        | 14.3 | 5.7  | 34.3 | 25.7 | 54.3 | 71.4        | 25.7 | 65.7 | 65.7 | 25.7 | 25.7 | 65.7        | 45.7 | 34.3 | 5.7  | 11.4 | 14.3 |
| Average            | 5.2         | 5.0  | 4.9  | 9.8  | 8.1  | 20.5 | 38.2        | 9.1  | 33.3 | 33.3 | 29.5 | 13.0 | 25.2        | 18.9 | 18.3 | 15.2 | 16.5 | 20.2 |

When the results were calculated, the False Acceptance Rates per user were averaged across all users to provide an average FAR for each metric. The averaged results for the statistical approach are shown in Table 6. It

should be noted that the keyword latencies did not use the unmatched alert increase due to the use of a word list/dictionary – i.e. many words would not be matched in the users' profile.

*Table 6. Final statistical results (best results highlighted)*

| Metric    | S.D. | Unmatched Alert | FAR   |
|-----------|------|-----------------|-------|
| Digraphs  | 0.6  | No              | 5.2%  |
|           | 0.6  | Yes             | 5.0%  |
|           | 0.7  | No              | 4.9%  |
|           | 0.7  | Yes             | 9.8%  |
|           | 0.8  | No              | 8.1%  |
|           | 0.8  | Yes             | 20.5% |
| Trigraphs | 0.5  | No              | 38.2% |
|           | 0.5  | Yes             | 9.1%  |
|           | 0.6  | No              | 33.3% |
|           | 0.6  | Yes             | 33.3% |
|           | 0.7  | No              | 29.5% |
|           | 0.7  | Yes             | 13.0% |
| Words     | 0.8  | No              | 25.2% |
|           | 0.8  | Yes             | 18.9% |
|           | 0.5  | No              | 18.3% |
|           | 0.6  | No              | 15.2% |
|           | 0.7  | No              | 16.5% |
|           | 0.8  | No              | 20.2% |

## 5. DISCUSSION

While the results shown in Table 6 show some encouraging FAR levels there is still significant variation with the best results obtained at 0.7 standard deviations for digraphs, 0.5 standard deviations for trigraphs (with increased alert levels for unmatched digraphs) and 0.6 for keywords. However, when the full results are considered (as shown in Table 5), even at the optimum settings, certain users show high FAR levels (e.g. user 23's profile returned FAR levels of 51.4%, 45.7% and 37.1% respectively for digraph, trigraph and keywords at the average optimum settings). It can also be clearly observed that the results for trigraphs and keywords are significantly worse when compared with those for digraphs – this is most likely to be related to the number of underlying samples used for these techniques (i.e. the number of sampled digraphs were significantly higher than that for trigraphs and keywords, with a corresponding increase of samples per digraph). It is probable that over a longer period of time, the profiles could be refined for trigraphs and keywords to produce a more distinct user profile with a corresponding reduction in the FAR.



These results also demonstrate that the techniques can be very effective for some users while very ineffective for others. For example, when considering digraph FAR's at 0.6 standard deviations (where 0% FAR was actually experienced for 19 out of the 35 users – 54.3%) the average FAR (5.2%) has been heavily influenced by a single user (user 23) whose 68.6% FAR dramatically increases the average. In a full implementation, the authors propose that the use of keystroke analysis should only form a part of a comprehensive user monitoring system. As such, a users' typing would only be monitored if the method was shown to be a discriminating authentication technique for that user. The removal of user 23 from the results in Table 5 significantly affects the average FAR's presented in Table 6, reducing the best digraph results from 4.9% to 3.5% , trigraph results from 9.1% to 8.0% and keywords from 15.2% to 14.5%.

Further optimisation can be achieved by removing the worst 5 participants (15%) from the trial results. This provides a significant improvement in the results of the technique with average FAR's as low as 1.7% for digraphs, 4.4% for trigraphs and 12.8% for keywords (Table 7). While the keyword FAR in particular remains unacceptably high, a reference back to Table 5 reveals that there were still almost a third of users for whom 0% FAR was observed at the 0.5 standard deviation threshold. This suggests a clear potential for using the technique in a subset of cases – which could also increase if additional keyword typing samples were obtained to support the profiling.

*Table 7. Optimised results*

| Metric    | S.D. | Unmatched Alert | FAR   |
|-----------|------|-----------------|-------|
| Digraphs  | 0.6  | No              | 1.7%  |
|           | 0.6  | Yes             | 2.4%  |
|           | 0.7  | No              | 2.2%  |
|           | 0.7  | Yes             | 7.0%  |
|           | 0.8  | No              | 4.9%  |
|           | 0.8  | Yes             | 17.0% |
| Trigraphs | 0.5  | No              | 34.5% |
|           | 0.5  | Yes             | 4.4%  |
|           | 0.6  | No              | 29.3% |
|           | 0.6  | Yes             | 29.3% |
|           | 0.7  | No              | 25.6% |
|           | 0.7  | Yes             | 10.6% |
| Words     | 0.8  | No              | 21.2% |
|           | 0.8  | Yes             | 15.2% |
|           | 0.5  | No              | 13.8% |
|           | 0.6  | No              | 12.8% |
|           | 0.7  | No              | 15.3% |
|           | 0.8  | No              | 19.7% |

The removal of a number of specific user accounts from the keystroke monitoring process is not an ideal solution to the problem of poor user authentication. Keystroke analysis is unlikely to be used as a sole-method of user authentication, instead, it is envisaged that the methods described in this paper would form a part of a larger authentication system and would be only one of a range of authentication metrics that each user could be monitored with. With a larger number of users (and hence a wider range of user typing abilities and corresponding authentication rates) there is likely to be a proportional increase in the number of users for whom keystroke analysis does not produce appropriate FAR/FRR rates – in these cases other, more appropriate, techniques would have to be used. Identifying the cause of poor user performance when using keystroke analysis is vital; on-going work within the authors' research group will conduct further analysis on the gathered data sets to try to determine the cause of the variation between users and identify common factors (e.g. users' typing abilities, differences between application usage etc.).

## **6. CONCLUSIONS**

It is clear from the results presented in this paper that there is considerable potential for continuous user authentication based on keystroke analysis. The long-term sampling of digraph keystrokes has served to reinforce the validity of the technique, while the introduction of trigraph and keyword monitoring has provided additional metrics that can be used as alternative (or complimentary) techniques. In particular, the use of keyword monitoring has considerable potential when used to monitor for specific, high-risk typed words (e.g. delete, format etc.).

It is also clear that the simple statistical approach does not provide sufficient distinction for all users and a live implementation would have to consider which metric (if any) is most appropriate for each user. It is envisaged that keystroke analysis would become only one of a number of monitoring characteristics used by a more comprehensive system with other authentication and supervision techniques.

Future work will also consider how the individual keystroke metrics can be combined together. For example, by combining the confidence measures of multiple metrics (e.g. monitoring digraphs and trigraphs), coupled with monitoring specific keywords (e.g. the typing patterns for high-risk words – format, delete etc.), it may be possible to provide a higher level of

confidence in the authentication of the user. The potential for this method will be considered in a later paper.

## 7. ACKNOWLEDGMENTS

The authors would like to thank the trial participants who assisted in the collection of the keystroke data. In particular, we would like to acknowledge the assistance of the staff and researchers of the Network Research Group, the Department of Psychology and the staff of TMA Global and John Nicholls Builders.

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# **Keystroke Analysis as a Method of Advanced User Authentication and Response**

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**Key words:** Keystroke Analysis, User Authentication, Biometrics, Intrusion Response.

**Abstract:** There has been significant interest in the area of keystroke analysis to support the authentication of users, and previous research has identified three discrete methods of application; static, periodic dynamic and continuous dynamic analysis. This paper summarises the approaches and metrics arising from previous work, and then proceeds to introduce a new variation, based upon application-specific keystroke analysis. The discussion also considers the use of keystroke analysis as a progressive, escalating response measure in the context of a comprehensive user authentication and supervision system, presenting an example of how this could be realised in practice.

## **1. INTRODUCTION**

The issue of user authentication in IT systems has long been recognised as a potential vulnerability, with the majority of current systems relying upon password methods. Such methods have been repeatedly proven to be open to compromise, and can also be considered problematic in the sense that they typically only serve to facilitate a one-off authentication judgement at the start of a session. A number of previous works [1, 2, 3] have

consequently discussed the need for some form of monitoring to continuously (or periodically) authenticate the user in a non-intrusive manner. Although such monitoring is technically feasible, there are significant issues to be considered in selecting appropriate attributes to assess. This is particularly important, as continuous monitoring must be transparent to the end user in order to minimise any perceived inconvenience (with the exception of appropriate challenges in the event of suspected impostor activity).

A number of studies have considered the application of keystroke analysis to the problem of inadequate user authentication in modern IT system using static [4, 5, 6] and dynamic [7, 8] implementations. While these studies have evaluated the effectiveness of the proposed solutions, none have considered the implementation and necessary supporting application framework to effectively use keystroke analysis as a viable authentication and supervision mechanism.

This paper summarises the potential approaches to keystroke analysis, and presents details of a new method based on application-specific user profiling. It then proceeds to consider how keystroke analysis may be utilised as part of an intrusion response framework.

## 2. KEYSTROKE ANALYSIS OVERVIEW

Previous studies have identified a selection of data acquisition techniques and typing metrics upon which keystroke analysis can be based. The following section summarises the basic methods and metrics that can be used.

- **Static at login** - Static keystroke analysis authenticates a typing pattern based on a known keyword, phrase or some other pre-determined text. The captured typing pattern is then compared against a profile previously recorded during system enrolment. Static keystroke analysis is generally considered to be an initial login enhancement as it can supplement the traditional username/password login prompt, by checking the digraph latencies of the username and/or password components (i.e. authenticating the user on the basis of both *what* they typed and *how* they typed it).
- **Periodic dynamic** - Dynamic keystroke analysis authenticates a user on the basis of their typing during a logged in session. The captured session data is compared to an archived user profile to determine deviations. In a periodic configuration, the authentication

judgement can be intermittent; either as part of a timed supervision, or, in response to a suspicious event or trigger. This method provides distinct advantages over the static approach. Firstly, it is not dependent on the entry of specific text, and is able to perform authentication on the basis of any input. Another factor is the availability of data; in static keystroke analysis, the range of digraphs and frequency of their occurrence is likely to be significantly limited compared with a dynamic approach. Even an inexperienced typist is likely to produce sufficient digraph pairs to allow an authentication judgement to be derived. This is an important factor as it is necessary to have a statistically significant volume of keystroke data in order to generate a user profile.

- **Continuous dynamic** - Continuous keystroke analysis extends the data capturing to the entire duration of the logged in session. The continuous nature of the user monitoring offers significantly more data upon which to base the authentication judgement. With this method it is possible that an impostor may be detected earlier in the session than under a periodically monitored implementation. On the downside, however, the additional processing required will add to the computational overhead of the supervision system.
- **Keyword-specific** - Keyword-specific keystroke analysis extends the continuous or periodic monitoring to consider the metrics related to specific keywords. This could be an extra measure incorporated into a monitoring system to detect potential misuse of sensitive commands. For example, under a DOS/Windows environment it may be appropriate to monitor the keystroke metrics of a user attempting to execute the FORMAT or DELETE commands. This could represent a significant enhancement, as a command with a high misuse consequence (e.g. DEL \*.\* ) is unlikely to cause sufficient profile deviation when observed from a system-wide context, due to the limited selection of digraphs. By contrast, static analysis could be applied to specific keywords to obtain a higher confidence judgement.
- **Application-specific** - Application-specific keystroke analysis further extends the continuous or periodic monitoring. Using this technique, it may be possible to develop separate keystroke profiles for distinct applications. For example, a user may be profiled separately for their word processing application and their email client. The potential of this new technique is discussed in more detail in section 3.

In addition to a range of implementation scenarios, there are also a variety of possible keystroke metrics that can be profiled as the basis for subsequent comparison:

- **Digraph latency** - Digraph latency is the metric that has traditionally been used for previous studies, and typically measures the delay between the key-up and the subsequent key-down events, which are produced during normal typing (e.g. T-H). In most cases, some form of low and high pass filter is applied to remove extraneous data from the session data.
- **Trigraph latency** - Trigraph latency extends the previous metric to consider the timing for three successive keystrokes (e.g. T-H-E).
- **Keyword latency** - Keyword latencies consider the overall latency for a complete word or may consider the unique combinations of digraph/trigraphs in a word-specific context.
- **Mean error rate** - The mean error rate can be used to provide an indication of the competence of the user during normal typing. Whilst this may not be user specific, it may be possible to classify users into a generic category, according to their typing ability, which can then be used as an additional authentication method.
- **Mean typing rate** - A final metric is that of the mean typing rate. As with the mean error rate, individuals can be classified according to their typing ability and hence evaluated based on their average typing speed.

While the final two metrics indicated above are unlikely to provide a suitably fine-grained classification of users for direct authentication judgements, they may be used to provide a more generic set of user categories that can contribute to a combined measure.

It should be noted that all of the above techniques and metrics can be implemented on a standard PC platform, without the need for special hardware.

### 3. EXPERIMENTAL DYNAMIC KEYSTROKE ANALYSIS

The idea of using keyboard characteristics for authentication is not unique, and there have been a number of previous published studies in the area. To date, however, virtually all published studies have focussed upon static or context-independent dynamic analysis, using the inter-keystroke latency timing method. From the earliest studies in 1980 [9], the focus has been on the analysis of digraph latencies. Later studies [6, 8] further enhanced the work, identifying additional statistical analysis methods that provided more reliable results.

In [7], the concept of dynamic keystroke analysis was first proposed, with the introduction of a reference profile that could be used to monitor a live user session. Brown and Rogers [5] also explored the idea of dynamic analysis, presenting preliminary results.

A summary of some of the main results from studies to date is presented in Table 1 below, which illustrates the effectiveness observed (in terms of false acceptance and false rejection errors), as well as the type of keystroke analysis technique employed (digraph/trigraph etc.) and the analysis approach taken (statistical/neural network etc.).

| Authors                                                                 | Method                                                               | %FAR                                  | % FRR                                   |
|-------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------|-----------------------------------------|
| Umphress & Williams (1985) [10]                                         | Digraph Statistical                                                  | 6%                                    | 12%                                     |
| Legget & Williams (1988) [11]                                           | Digraph Statistical                                                  | 5%                                    | 5.5%                                    |
| Joyce & Gupta (1990) [6]                                                | Digraph Statistical                                                  | 0.25%                                 | 16.67%                                  |
| Bleha et al. (1990) [12]                                                | Digraph Statistical                                                  | 2.8%                                  | 8.1%                                    |
| Legget et al. (1991) [7]<br><sup>1</sup> Static, <sup>2</sup> Dynamic   | Digraph Statistical                                                  | 5% <sup>1</sup><br>12.8% <sup>2</sup> | 5.5% <sup>1</sup><br>11.1% <sup>2</sup> |
| Brown & Rogers (1993) [5]<br><sup>1</sup> Group 1, <sup>2</sup> Group 2 | Digraph<br>Combined Neural<br>Network & Statistical                  | 0%                                    | 4.2% <sup>1</sup><br>11.5% <sup>2</sup> |
| Napier et al. (1995) [13]                                               | Digraph Statistical                                                  | 29.5% / 3.8%                          |                                         |
| Mahar et al. (1995) [8]                                                 | Digraph Statistical                                                  | 35% / 17.6%                           |                                         |
| Furnell et al. (1996) [14]<br><sup>1</sup> Static, <sup>2</sup> Dynamic | Digraph<br>Neural Network <sup>1</sup> ,<br>Statistical <sup>2</sup> | 8% <sup>1</sup><br>15% <sup>2</sup>   | 7% <sup>1</sup><br>0% <sup>2</sup>      |

Table 1: Previous keystroke analysis studies



A further variation in the data analysis can be introduced through the consideration of application specific keystroke profiles. If we accept from previous work that individual users have a distinct typing pattern, it can be hypothesised that an individual's typing pattern may also vary depending upon the application in use. For example, a user participating in a chat session may type in a fairly relaxed style, while the same user may type in a significantly different way when producing a document. It should also be noted that certain categories of user might use the numeric keypad for large quantities of data entry. Under these circumstances the volume and diversity of the keystroke digraphs will vary tremendously when compared to the more usual alphanumeric typing encountered with most user profiles. Previous research has been carried out in this area [15], which has shown that analysis of numeric keystrokes can provide a viable authentication measure. This is an area receiving on-going attention through a separate research project at the authors' institution.

In [16] the authors described a trial in which keystroke data, obtained within Microsoft Windows NT, was evaluated across all applications. While the results from this trial were encouraging, the quantity of data collected was insufficient to make a true, statistically valid, conclusion. Instead it was determined that further trials were necessary. Following the first trial, the authors conducted a second round of monitoring in which eight test subjects were profiled. Over a period of 3 months, a total of 760,000 digraph samples were captured and stored for analysis. In this case, however, the analysis was conducted with a view to determining viability of application-specific keystroke profiling. To this end, it was necessary to identify a series of applications for profiling, with the selection criteria being those for which sufficient keystroke data had been logged during the sampling period. A review of the keystroke data revealed that the applications satisfying this requirement were Microsoft MSN Messenger, Internet Explorer, Word and PowerPoint. While the authors considered that a numerically intensive application such as Excel would have provided an interesting candidate, insufficient keystrokes were captured to enable the creation of a profile. Additionally, of the eight users sampled during the trial, only five produced sufficient data to analyse from all of the aforementioned applications. Although the resulting sample group was very small, it was sufficient to yield interesting results in relation to an initial assessment of application-specific profiling.

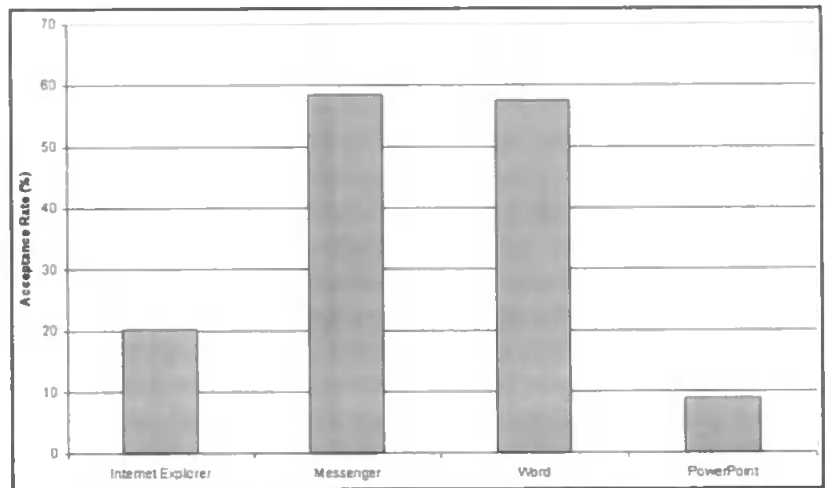


Figure 1: Acceptance Rate for application specific keystroke data compared against a system-wide context user profile

In Figure 1 above, a single user's application-specific keystroke data is compared against the reference profile from the same user. The reference profile was based on all keystroke data acquired from all applications. Although the figure does not show distinct differences in all cases, there is a clear distinction between all applications apart from Messenger and Word. This can be explained when the nature of these applications is considered. Messenger and Word are both significantly textual in their usage, and users will typically type within Messenger and/or Word for considerable periods of time. In contrast, while Internet Explorer and PowerPoint sessions may both involve significant elements of keyboard activity, the typing is more likely to occur in sporadic bursts. As such, any dynamic that emerges is likely to be markedly different to that which would emerge in applications where more sustained typing is the norm. Considering the information portrayed above, the creation of application specific profiles would be likely to increase the acceptance rates observed.

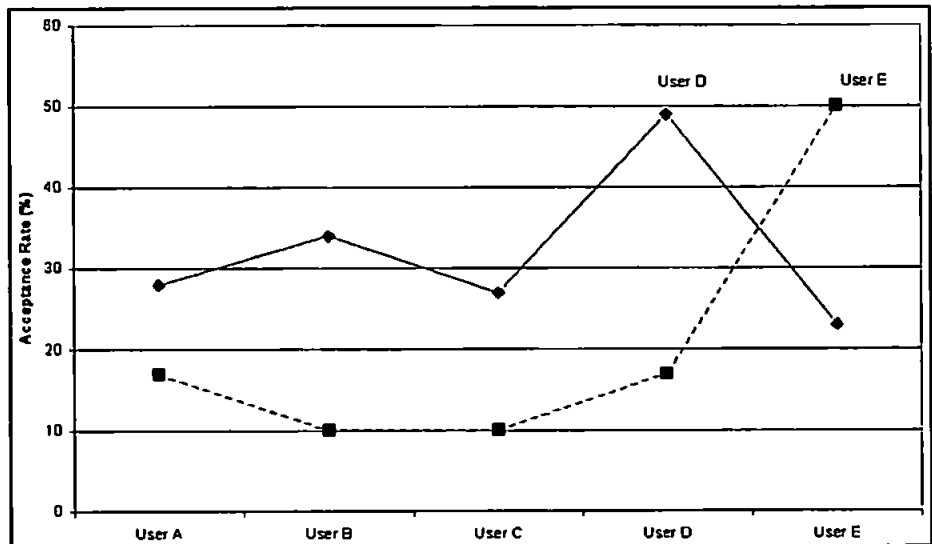


Figure 2: Acceptance Rate for two user profiles

In Figure 2 above, a specific users' profile (users D and E when using Internet Explorer) is examined, showing there is a clear difference between other users' keystroke data (impostors) with appropriate peaks in acceptance rate for the valid users.

While the results shown do not indicate a suitably discriminative metric upon which to base a satisfactory authentication judgement, they do show a level of correlation between a user's typing pattern in an application-specific context. These preliminary results show that further work is needed to investigate the use of application-specific keystroke analysis.

#### 4. AN ESCALATING RESPONSE FRAMEWORK USING KEYSTROKE ANALYSIS

The earlier discussion summarised the different potential implementations of keystroke analysis, and explained the operational differences between the approaches. It is possible to integrate these analysis approaches into an overall user authentication and supervision framework, with the varying techniques being invoked as responses to anomalies detected at earlier stages. A possible example of this is illustrated in Figure 3, which shows how the five variations discussed earlier can be incorporated within a four-level response framework. It should be noted that this is by no means the only method by which the techniques could be combined, and

specific implementations could vary depending upon rule sets for a particular user, class of users, or general organisational security policy.

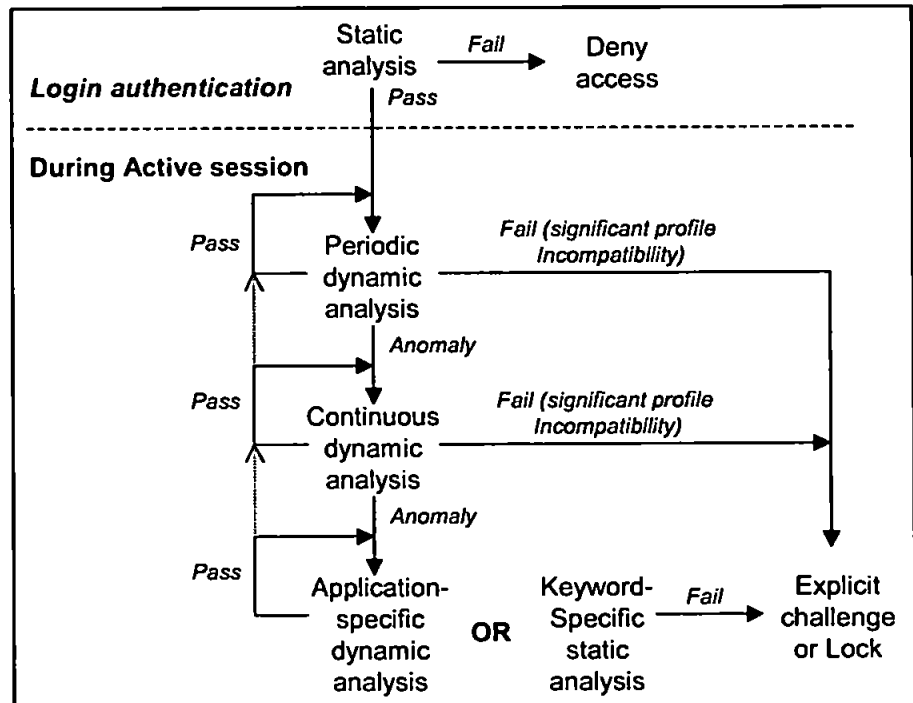


Figure 3: Response framework using keystroke analysis

A suitable architecture for achieving such an approach is offered by the Intrusion Monitoring System (IMS) [17]. This proposes an architecture for real-time user authentication and misuse detection, based upon a monitoring *Host* that has the responsibility for supervising a number of *Client* systems (e.g. in the form of end user PCs or workstations). Key elements of the architecture, from the perspective discussed in this paper are the *collector* (which obtains the keystroke data from the individual client systems), the *anomaly detector* (which performs the actual keystroke analysis and profile comparison, maintaining a consequent alert status metric), and the *responder* (which is responsible for initiating the different keystroke analysis approaches in response to increases in the alert status and other contextual factors). Assuming such a monitoring context, the text below describes how the response process in Figure 3 would proceed.

Initial authentication may occur using a standard username/password pair, but supplemented by the use of static keystroke analysis to assess how the information is entered. If the user fails to authenticate at this stage (e.g. after being permitted three attempts to enter the details), then the most appropriate

response is to deny access (if the correct password is provided, but the keystroke analysis aspect fails, then an alternative option could be to allow the login to proceed, but to begin the session with a higher level of subsequent monitoring – e.g. continuous rather than periodic assessment). If this login authentication is successful, the user will proceed to a logged in session, during which dynamic keystroke analysis could be applied on a periodic basis (in order to minimise the associated processing overhead in the initial instance). Assuming no anomalies, this could simply continue throughout a logged in session. If a departure from the typing profile is noted during the monitoring period, however, there would be two options for response. If the keystroke data exhibits a significant incompatibility, then a high confidence of impostor action could be assumed and the responder could proceed directly to some form of explicit action (e.g. interrupting the user session by issuing a challenge or suspending their activity pending an administrator intervention). In cases where the profile incompatibility is not conclusive, the responder could initiate an increase in the monitoring resolution – firstly to invoke continuous dynamic analysis, and then beyond this to invoke either application or keyword-specific methods. The choice in the latter case would depend upon the context of the current user's activity. For example, if they were word-processing, then application-specific dynamic analysis would potentially give a more accurate assessment of identity. If, by contrast, they were operating at a command line level, then it could be considered more appropriate to invoke keyword-specific static analysis, looking for instances of particularly sensitive commands such as 'format' or 'erase'. Profile incompatibility at this final stage would automatically result in more explicit response action.

In cases where the responder agent has initiated a more detailed level (e.g. from periodic to continuous, or from continuous to application-specific), then the monitoring would continue at this level for a period of time, in order to ensure that profile incompatibilities were no longer observed. A suitable trigger (e.g. the entry of a certain number of further keystrokes without significant profile departure) would be used to reduce the alert status of the monitoring system, and thereby allow the responder agent to re-invoke a lesser level of analysis (this is indicated by the dotted arrow lines in the figure).

The combination of mechanisms in this manner allows a system to provide a standard, and hence acceptable, user login for the initial authentication, while also providing enhanced user supervision for the duration of the users' session. Such a system should, in theory, ensure transparent operation to legitimate users. It should also be noted that, in a practical context, keystroke analysis may not be the only technique involved, and other metrics relating to user activity and behaviour might also be

considered by the *anomaly detector*, and thereby used to inform the *responder agent*.

## 5. CONCLUSIONS

This paper has considered the significant variety of implementation methods and metrics that can be associated with keystroke analysis. The new concept of application-specific analysis has been introduced, along with initial experimental findings that support the feasibility of the approach. The preliminary results suggest that the technique is worthy of further investigation.

The discussion has also considered the application of keystroke analysis as a response mechanism within an intrusion detection system. The combination of analysis techniques, placed within such an authentication/supervision framework has the potential to provide a significant improvement in system-wide security against impostor attacks, as well as ensuring transparency to legitimate end users.

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# **A Preliminary Investigation of User Authentication Using Continuous Keystroke Analysis**

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**Key words:** Keystroke Analysis, Authentication, Biometrics, Data Mining.

**Abstract:** There has been significant research in to the provision of reliable initial-login user authentication, however there is still a need for continuous authentication during a user session. This paper presents a series of results from the preliminary statistical analysis of multi-application keystroke data. This has been contrasted with a Data Mining approach to the production of a unique user profile. This paper aims to determine which approach provides the best basis for further research. It is determined that the technique offers promise as a discriminator between individuals in an operational context, but further investigation with larger data sets is required with a combination of approaches being considered in order to improve the accuracy.

## **1. INTRODUCTION**

There have been a number of previous studies that have considered the security weaknesses in modern IT system and, whilst various recommendations and technical solutions have been proposed, many still



rely on enhancing the initial login-stage mechanism (e.g. via biometric identification, smart cards etc.) [COPE 90, SHER 92, MILL 94]. Whilst this improves the initial authentication judgement, there is still a need for user authentication throughout a session. In most systems there is no further check on a users' identity beyond the initial username/password. Once a user gains legitimate access to IT resources, it is feasible for there to be no further challenge, with the only possibility for detection of a masquerader being the post-event detection of a major incident (i.e. an impostor can masquerade as the valid user without detection or challenge).

To counter this risk, it is suggested that some form of user monitoring is desirable to continuously (or periodically) authenticate the user in a transparent manner. Whilst such monitoring is technically feasible, there are significant issues to be considered in selecting appropriate attributes to assess. This is particularly important, as continuous monitoring must be transparent to the end user in order to minimise any perceived inconvenience (with the exception of appropriate challenges in the event of a significant profile deviation).

This paper specifically considers the problems of continuous user authentication using keystroke digraph latencies. This area has not received much attention and as such, most of the background research is based upon static keystroke analysis [JOBU 89, BROW 93, JOYC 90] (i.e. where the users' typing was constrained). Keystroke analysis is, however, considered by end users as the most acceptable form of continuous authentication [FURN 00]. A GUI environment produces a new challenge, as there is no option to control the users' typing. This can cause problems, as it is difficult to determine in which application individual digraph pairs were entered. This paper will introduce a statistical approach for detecting deviation from a user's historical keystroke profile captured under a multi-tasking windowed environment. Following this initial analysis, a Data Mining (DM) approach will be considered in order to determine the potential for improving user classification. It should be noted that the aim of this paper is to determine which approach provides the best basis for further research and is not intended as a thorough analysis of keystroke latencies for user authentication. Finally, some thoughts on future work are introduced which will be developed further.

## **2. EXPERIMENT OVERVIEW**

Although there have been a series of papers describing the mechanisms for keystroke analysis, the authors have been unable to identify any research specifically focussed on continuous keystroke analysis in which the

collection of users typing samples was not artificially constrained in some way through a custom interface (e.g. asking the user to type known strings).

The experiment was designed to allow keystroke data to be collected under the Microsoft Windows NT environment. In order to collect the required data, it was necessary to implement a mechanism for acquiring keystroke notifications across all applications running within a users' active session. As the client systems were running Microsoft Windows NT v4.0, it was necessary to implement a system-wide hook function that would receive keyboard events through the Windows message chain. System-wide hooks allow a specified code block (hook-function) to receive the appropriate Windows messages (e.g. WM\_KEYUP for the key-up event) irrespective of the target application (i.e. it is possible for a hook function residing in a system DLL to receive keystroke notifications for all currently running applications). This effectively allowed application keystroke data to be duplicated and directed towards the data logger on the client workstation. Technical details of the implementation of the hook function and its associated support files are beyond the scope of this paper and, as such, have been omitted. There are a number of resources available that provide further information for interested readers [DOWL 00, MICR 00]. In order to determine accurate digraph latencies, it was also necessary to implement a high-accuracy timer (as the default timers available do not offer adequate accuracy for the millisecond latencies expected).

To eliminate extreme short/long digraph latencies that may adversely affect the distribution of digraph times, any digraph pair whose latency fell outside a nominal range was excluded from the archived data. For the purposed of this experiment the range was restricted to times above 40ms and below 750ms. These thresholds are based on the original experiments carried out by the authors [FURN 95] and are designed to eliminate samples where two keys may have been accidentally struck together (thus, producing an infeasibly small latency) or, where the user may have made a pause in their typing and thus introduced an unnaturally large inter-keystroke latency. The output of this pre-processing was a data file containing the following structure:

| <i>first_char</i> | <i>second_char</i> | <i>digraph_latency</i> |
|-------------------|--------------------|------------------------|
|-------------------|--------------------|------------------------|

For this experiment a total of ten users were profiled. As the intention was to evaluate the analysis mechanisms without implementing a large-scale trial, tests were carried out using a small set of test subjects. The main limiting factor was the need to collect data over a prolonged period (weeks rather than hours). Despite the small scale of the trial, it still proved difficult to collect sufficient data in order to provide a valid comparison between users. Due to this limited set of data, analysis has focussed on the 4 main

users who provided the largest profiled data sets in order to best illustrate the trends observed.

### 3. STATISTICAL ANALYSIS

Following the pre-processing described in the previous section, the experimental data for each user was then processed off-line to calculate the mean and standard deviation values for each unique digraph pair. In the event that any digraph pair had a standard deviation greater than its mean value, the digraph samples were sorted and the top/bottom 10% were then removed with subsequent re-calculation of the mean and standard deviation values – this was only attempted where at least ten samples were available for the digraph pair. The reason for this additional step was to remove digraph samples where the latencies would have an adverse affect on the standard deviation (i.e. the distribution of samples was tightened).

Once a set of digraph pairs was produced (with corresponding mean/standard deviation digraph latency values), the user's profile was further constrained by filtering out digraph pairs where the sample count fell below a nominal threshold value. Our experiments fixed this value at fifty samples; however, the software used for analysis allows a variable threshold that will be investigated further in the future work described in a later section. A summary of the profiles generated by this method is shown in *Table 1*.

*Table 1: Summary of user profile statistics*

| User   | Unique Digraph Pairs | Filtered Digraph Pairs | Average Typing Speed |
|--------|----------------------|------------------------|----------------------|
| User A | 466                  | 122                    | 151ms                |
| User B | 405                  | 51                     | 145ms                |
| User C | 412                  | 89                     | 206ms                |
| User D | 461                  | 127                    | 162ms                |

Once a user profile was generated, the profile was evaluated by comparison with the users' raw keystroke data. This allowed the test profile to be evaluated using the users' own data (to test the False Rejection Rate – FRR) and against other users' keystroke data (to test the False Acceptance Rate – FAR).

As there is likely to be significant variation in a users' own session data, a compensatory factor was applied to the standard deviation that could be varied in a "live" environment according to the security needs of the organisation. This factor allowed the number of standard deviations from the

mean to be adjusted. For the purposes of this experiment, four weightings were considered, namely 0.5, 1, 1.5 and 2. This produced an acceptable digraph range:

$$\text{digraph range} = \text{mean} \pm (\text{standard deviation} * \text{weighting factor})$$

When viewing the preliminary results (Figure 1), if we consider the four users A, B, C and D and follow the vertical columns of data, we can see a clear peak for each users data when compared with their own profile. This is most noticeable for user C where a significant peak is observed (50% of all digraphs accepted) compared with 35% when user B's digraph data was tested against the same profile.

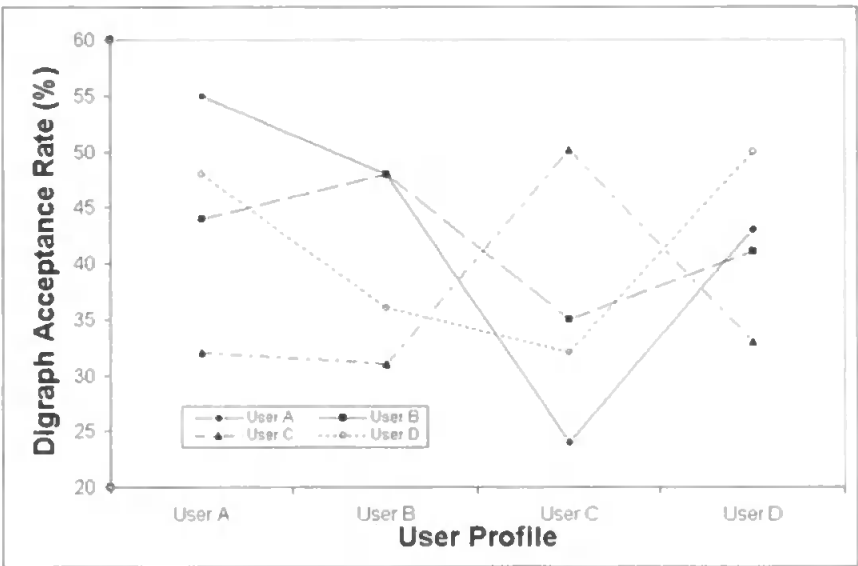


Figure 1: User profile comparisons

Although there was a clear correlation between user C's profile and data, if we consider user A, there was a high FAR for data from users D and B (impostors) when compared with user A's profile. We can also see that in user B's profile the impostor "user A" achieved the same acceptance rate (48%). It is clear from these results that an additional measure of acceptance/rejection is required. To further test the FAR/FRR of the test system, the analysis software monitored the number of consecutively rejected digraph pairs – representing the highest alert level of the system (Figure 2).

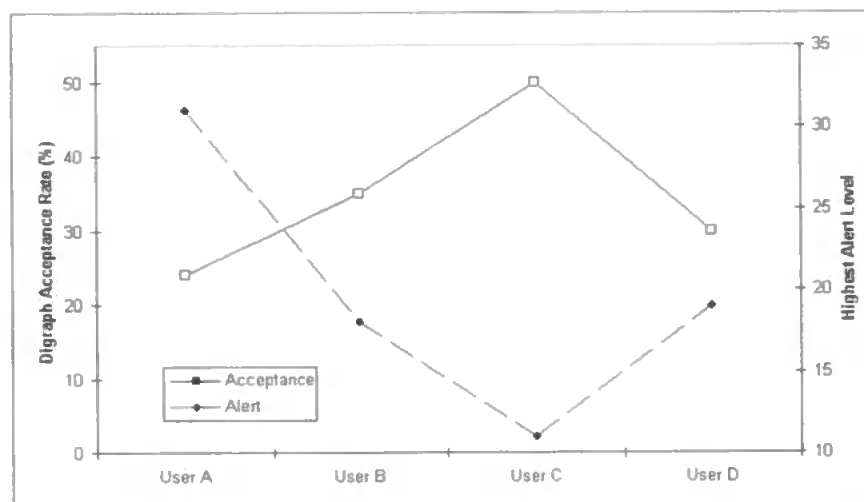


Figure 2: Single user profile comparison

When considering (Figure 2) we can identify two distinct trends. Firstly, the top line plots the digraph acceptance rate for all user data sets against user C's profile. Here we can see a clear peak correlating to user C's own data and corresponding reductions in the acceptance rates for the other users' data. Secondly, the lower line indicates the highest alert level detected by the analysis software. This is simply a record of the highest count of consecutively rejected digraph times (excluding non-profiled digraph pairs). Again, we can see a correlation between user C's own data when compared with their profile and corresponding increases in the alert level as impostor data sets are compared with the target profile.

#### 4. DATA MINING ANALYSIS

The methodology described in the previous sections, using traditional statistical approaches, requires a significant level of manual intervention in the data analysis stages. Further, it is time consuming when considering the amount of data generated from a single session or multiple sessions and the number of users on a system. From this we can determine there is a need to automate some of the data analysis pre-processing stages. These stages offer the opportunity to investigate Data Mining (DM) methodology and algorithms, a previously untried approach in this field, in order to eliminate the manual approaches adopted and also to compare the FAR/FRR percentage accuracy with the statistical approach. Data Mining can be described as a collection of techniques and methodologies used to explore

vast amounts of data in order to find potentially useful, ultimately understandable patterns [FAYY 96] and to discover relationships. The methodology used to analyse the raw keystroke data is derived from the four main activities of DM; selection, pre-processing, data mining and interpretation [FAYY 96]. DM is an iterative and interactive process, involving numerous steps with many decisions being made by the user. Different algorithms are optimised based on the predefined DM task. This involves deciding whether the goals of the DM process are classification, association, or sequential [MICH 94].

For the purpose of this work, the data sets were split into a ratio of 9:1 hence into two parts; a training set and a testing set, which is a commonly used technique known as train and test. The Intelligent Data Analysis (IDA) Data Mining Tool [SING 99] is used to analyse the sample data sets which incorporates algorithms from the fields of Statistical, Machine Learning and Neural Networks. Six algorithms, k-NN, COG, C4.5, CN2, OC1 and RBF were chosen for this investigative work. The algorithm or classifier is subjected initially with the training set and then the classification accuracy is tested using the unseen data set or testing set. The results give an indication of the error rate (or FAR) and the overall classification accuracy of the trained algorithms.

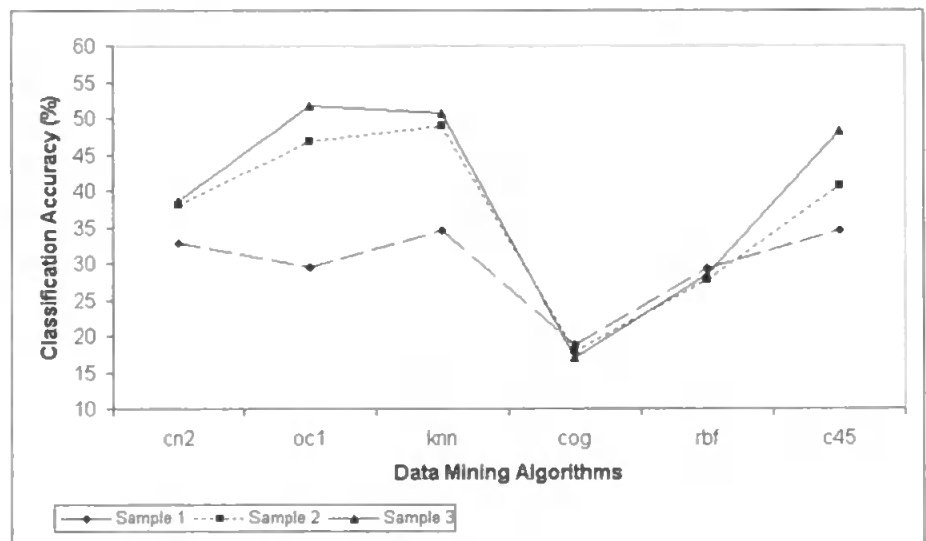


Figure 3: Varying sample sizes with fixed number of classes and attributes

The percentage classification accuracy obtained is encouraging as depicted in (Figure 3), which shows that when the sample size is increased, the classification accuracy obtained increases proportionally, except for the

COG a statistical based algorithm and RBF a Neural Network based algorithm. This is important when considering the size of data being analysed and hence eliminates the ad-hoc approaches adopted using traditional statistical methods.

The initial results suggest that Machine Learning (OC1 and C4.5) and Statistical (k-NN) based algorithms are suitable for these types of data sets. Despite the results, more work needs to be carried out in order to correlate the results to a specific or group of algorithm(s), in order to obtain a higher percentage of classification accuracy.

## 5. CONCLUSIONS

It is clear from the results presented in this paper that there is some potential for continuous user authentication based on keystroke analysis. However, it is also clear that a simple statistical approach does not provide sufficient distinction between users. The DM approach is limited due to the nature of the data gathered and will also require further research. It is proposed that further work will investigate the usefulness of trigraph keystroke combinations (timings for three consecutive keystrokes) and the possible use of word-graph timings (timings for frequently occurring words). Further analysis will be carried out on much larger data sets in order to give a higher statistical reliability and will also incorporate high-level characteristics (average typing speed and typing error rates) which will provide additional information to the system-characteristic based DM approach being developed in parallel with this research [SING 01]. Other approaches that will be investigated include, consideration of various standard deviation weightings, varying the minimum number of samples for profiled digraphs and varying the inclusion threshold for each sampled digraph. A further possibility for research may be an investigation into a correlation between digraph latencies and the applications in which they were generated (i.e. application specific keystroke profiles).

This paper has presented a series of results from the preliminary statistical analysis of multi-application keystroke data. This has been contrasted with a DM approach to the production of a unique user profile. Whilst the results from this stage of the research are not as encouraging as we had hoped for, they have shown a potential for the use of continuous user authentication. The next phase will concentrate on a combination of techniques to improve the digraph acceptance rate seen in these results.

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# **Authentication and supervision: A survey of user attitudes**

S.M. Furnell, P.S. Dowland, H.M. Illingworth and P.L. Reynolds

## **Abstract**

User authentication is a vital element in ensuring the secure operation of IT systems. In the vast majority of cases, this role is fulfilled by the password, but evidence suggests that this approach is easily compromised. Whilst many alternatives exist, particularly in the form of biometric methods, questions remain over the likely user acceptance. This paper presents the results of a survey that examines user attitudes towards a range of authentication and supervision techniques. It is concluded that whilst there is still an element of reluctance amongst users to depart from the familiar password based mechanisms, many are convinced of the need for improved authentication controls. The acceptability to users of various new techniques is variable, but many seem willing to consider a range of alternative methods.

## **Keywords**

Authentication, Biometrics, User supervision, Survey.

## **Introduction**

User authentication is widely accepted to represent an essential first line of defence in the security of Information Technology (IT) systems. All but the most trivial systems, therefore, require some form of authentication in order to verify that a claimed user identity is indeed correct. There are three main approaches to user authentication: something the user knows (e.g. password or PIN), something the user has (e.g. a card or other token) and something the user is (e.g. a biometric characteristic) [1]. By far the most commonly used means of authentication in IT systems is the password. Passwords are conceptually simple for both system designers and end users, and can provide effective protection if they are used correctly. However, the protection provided is often compromised by users themselves. Typical problems include forgetting passwords, writing them down, sharing them with other people and selecting easily guessed words.

If the password approach is to be replaced or supplemented, then alternative means of authentication are clearly required. However, when considering such alternatives, a number of factors can be cited that may complicate their adoption:

- effectiveness (i.e. the ability to detect impostors, whilst allowing legitimate access);
- cost (i.e. financial overheads of deployment);
- user acceptance (i.e. the friendliness and transparency of the measure).

Of these, the issue of user acceptance is possibly the most difficult to assess, as it represents a highly subjective measure. This paper presents the results from a survey that set out to assess public attitudes to various forms of user authentication and, thereby, determine whether acceptable alternatives to the password could be identified. The discussion begins by summarising the potential problems with existing password approaches and then proceeds to consider the alternatives that are offered by various classes of biometric method. Details of the survey itself are then presented, leading into an analysis of the results obtained.

## The problems with passwords

The password approach has a number of shortcomings, which can undermine the effectiveness of the approach [2]. Indeed, passwords can often be considered a mere hindrance to a determined hacker and can easily be bypassed by relatively inexperienced individuals using tools freely available on the Internet.

Several studies have been carried out over the last 20 years looking at the ease with which passwords can be determined. In 1979, 86% of the 3829 passwords gathered, could be guessed by a PC in less than one week [3]. This was later repeated by Klein in 1990 [4] and Spafford in 1992 [5]. Whilst the results from these subsequent experiments showed that password selection had improved (only 21% could be guessed in a week), so have the tools that can be used to *guess* them. In 1998, L0pht Heavy Industries released L0phtCrack [6], a utility which allows Windows NT Server Message Block (SMB) password packets to be captured during network authentication sessions. This utility not only allows the encrypted passwords to be captured directly off the network, it can also perform a dictionary and brute force attack against the encrypted passwords. Similar utilities are also available for other operating systems - most notably CRACK which runs under a number of flavours of UNIX [7].

There are a number of measures that can be taken to improve password security. For example:

- *Non-Dictionary words.* Forcing users to select non-dictionary passwords prevents the use of dictionary based attacks. Such attacks can identify a password in less than 20 minutes even on dictionaries with up to one million words. The only way to identify non-dictionary passwords is using a brute-force approach (testing every combination of characters for every length of password).
- *Passwords with mixed case/symbols.* Including both upper/lower case and symbols (!£\$% etc.) in passwords requires any attack to use a brute force method and increases the number of character permutations that must be tried.
- *Password ageing.* Should an intruder obtain a valid username/password combination, most systems will allow them to continue to access the system until the intrusion is noticed. If a password ageing policy is in place users can be forced to change their passwords regularly, thus forcing the intruder to identify the new password.

Although these suggestions will help to make a password-based system more resilient to an intruder they are by no means secure. A determined intruder can utilise password cracking utilities to determine even the most random password in a matter of weeks. With the advent of more powerful processors, intruders can crack passwords in a more realistic time – a matter of days for some PCs. In addition, it can be argued that restrictions such as those above may compromise the simplicity (and, hence, user friendliness) of the password method – one of the previously cited advantages. To counter these problems with password based systems, it is necessary to consider alternative approaches to user authentication.

## **An overview of biometric authentication approaches**

Whereas the password approach relies upon something the user *knows*, biometric authentication is based upon something the user *is*. This has the advantage that it is less straightforward for the user to be impersonated or to compromise protection themselves (e.g. they cannot share, write down or forget a biometric characteristic).

Methods of biometric authentication fall into two distinct categories, namely physiological and behavioural characteristics [8].

- Physiological biometrics represent those traits that describe who we are based on physical attributes, for example fingerprints, hand geometry, retinal and iris scanning. These characteristics usually require additional equipment to be connected externally to the computer to provide the necessary data capture.
- Behavioural biometrics encompass attributes such as typing style, voice pattern and signature recognition. Most behavioural characteristics can be acquired without the need for external equipment (e.g. keyboard & mouse), although some do require specialised hardware solutions (e.g. signature recognition).

Most biometric devices offer a compromise between high security/low user acceptance and low security/high user acceptance. This trade-off can be measured as the False Acceptance Rate (FAR) and False Rejection Rate (FRR) of the devices. It has so far proved impossible to achieve a system where the FAR and FRR are simultaneously reduced to zero, as they share a mutually exclusive relationship [9]. Most systems select an appropriate level at which inconvenience to the user, through denial of access (false rejections), is acceptable, without allowing too many intruders unauthorised access (false acceptances). All systems have an Equal Error Rate, the point at which the FAR and FRR rates are equal. Whilst this rate represents the theoretical “best-fit” for security measures, it is rarely ideal in a secure environment where a preference for either high FAR or FRR exists.

In recent years, biometric techniques have progressed from the research environment to consumer products. Indeed, Microsoft Windows now incorporates a biometric application programming interface to enable easy integration and utilisation of such approaches within the operating system [10]. Some biometrics are, however, more mature and well-known than others. The table below presents a list of biometric

techniques and accompanying descriptions (these descriptions are worded as presented to the respondents in the survey that is described in the next section).

| Method               | Description                                                                                                                                |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Keystroke analysis   | Research has shown that users have different typing styles and that they can be identified by measuring the times between keystrokes [11]. |
| Face recognition     | A snapshot of the user, taken by a camera positioned on the monitor, is compared with a previously stored 'faceprint'.                     |
| Mouse dynamics       | Similar to keystroke analysis, users can be identified by the way in which they use the mouse.                                             |
| Voice verification   | A user's voice, when speaking a word or phrase into the computer's microphone, is compared with a previously stored 'voiceprint'.          |
| Signature analysis   | A user signs their name using a special pen and pad, the signature is digitised and compared with a previously stored version.             |
| Iris scanning        | A snapshot of the user's iris, taken by a camera, is compared with a previously stored image.                                              |
| Hand geometry        | This technique measures the physical dimensions of the hand using a small camera and compares these with previously stored values.         |
| Fingerprint analysis | An automated version of the fingerprint identification system similar to that traditionally used in criminology.                           |

**Table 1 : Biometric methods, as presented to survey respondents**

Many organisations are already testing such alternative forms of user authentication. For example, trials of iris recognition systems have been conducted in the banking sector for use in automated teller machines [12].

A subset of the above biometrics (e.g. keystroke analysis, mouse dynamics) can be considered to represent aspects of the wider issue of behaviour monitoring. This recognises that everyone has characteristic ways of doing things and that, over time, it may be possible to establish individual profiles of behaviour. IT systems offer a number of factors that may be monitored in order to establish such a profile. Examples include:

- typical access time and location;
- operating system command usage;
- typical application and resource utilisation;
- methods of user interaction.

Techniques such as these have been incorporated into a variety of intrusion detection and monitoring systems, which can provide real-time supervision of user activity in order to detect potential impostor activity and other forms of misuse [13]. Although such an approach represents an increase in the level of security, there is also the potential to alienate legitimate users, who may be concerned about their activities being monitored to this level.

A significant body of work exists in relation to biometrics and behavioural monitoring systems and, as previously mentioned, many commercial products are now available as alternatives to simple passwords. It is, therefore, relevant to consider what the views of the potential users themselves are towards the technologies. This issue is explored in the sections that follow.

## **A Survey of attitudes towards authentication technologies**

In order to determine the acceptability of user authentication and supervision techniques, a survey was conducted to assess the attitudes and awareness of the general public. The survey aimed to assess the following issues:

- public attitudes towards different forms of user authentication;
- the attitudes towards the concept of continuous monitoring.

The survey questionnaire consisted of 53 main questions, the majority of which were multiple choice, with the remainder requiring short written responses. Many of the questions contained multiple sections, resulting in a maximum of 130 possible answers per respondent. The survey was split into a number of categories, each focussing on a specific area of interest to the authors. Questions 1-7 gathered general details, to determine the gender, age, education, and level of computer use; these provided demographic information on the survey response base. Questions 8-14 considered the use of computers within the respondent's work environment, whilst questions 15-19 considered the use of computers at home. These helped to provide information on the spread of IT into the home and work contexts, as well as the likely IT awareness of the respondents. Questions 20-34 were intended to determine individual opinions and knowledge in the area of computer crime and abuse. The final section (encompassing questions 35-53) looked at the respondent's views on user authentication and supervision. This paper targets the issues of user authentication and supervision, whilst the findings relating to computer crime have been documented in a previous publication [14].

The survey was distributed to a wide range of individuals and organisations with the intention of gaining a diverse variety of opinions. The questionnaire was made available in two forms, a printed copy and an online version published on the authors' WWW site. Approximately 300 printed surveys were distributed with 148 completed responses being received, representing a response rate of 49%. A further 27 surveys were submitted via the web site resulting in a total of 175 responses. It should be noted that, whilst questionnaires were sent to companies, the focus required respondents to reply from an individual rather than organisational perspective. As

such, these responses were still representative of a public rather than business viewpoint on the issues.

## Analysis of results

### General

The vast majority (80%) of the survey respondents were male. In terms of age, 74% of the respondents were below 35, indicating that the vast majority of the responses were likely to be from people who had ‘grown up’ with IT to some extent. The overall breakdown of respondents by age group is given in table 2.

| Age range   | Respondents |
|-------------|-------------|
| 16 to 24    | 42%         |
| 25 to 34    | 32%         |
| 35 to 49    | 18%         |
| 50 to 64    | 7%          |
| 65 and over | 0%          |

Table 2 : Survey respondents by age

In terms of employment background, a high number of responses were received from the technology fields (with 103 out of the 175 responses claiming to be from the computing, communications or engineering domains). Academically over 70% of the respondents claimed to hold post-16 qualifications, with 44% having a degree level education. This represents a high level of academic achievement among the respondents and reflects the fact that the distribution of a large proportion of surveys occurred via academic channels.

The respondents had considerable familiarity with IT, with over 98% having used a computer for over one year, 88% using a computer at work and 84% using one at home. The respondents were also asked about the availability of Internet access. 129 respondents (88%) claimed to have access at work, while 69 respondents (48%) claimed to have access at home.

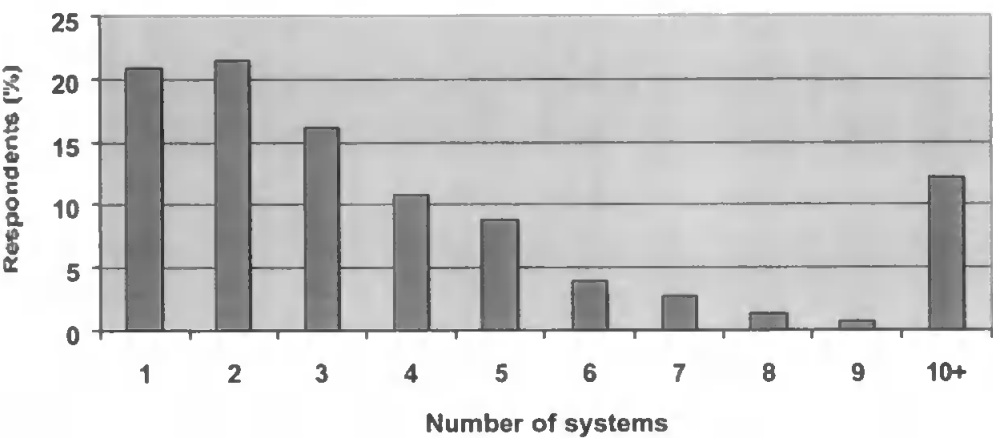
The information above indicates that the respondents were generally IT literate and had considerable experience using computers in both home and work environments. As later sections of the survey looked at views on user authentication and supervision in relation to such systems, it was felt that the respondents were suitably qualified to comment on these issues.

### Password based authentication

Given that they represent the most common (and, hence, familiar) form of authentication, the survey began by assessing respondent attitudes towards passwords. The results indicated that over 91% of respondents relied on passwords for access

control to their computers, a figure that is generally compatible with the 1998 KPMG security survey, which showed 97% of organisations using them [15].

Due to the dominance of passwords, most users have multiple passwords for different systems and applications. When asked how many different systems or applications they use which require passwords, 26% of respondents claimed to have five or more, with 18 people claiming in excess of ten (see figure 1).



**Figure 1 : Number of different systems/applications used requiring passwords**

The requirement to remember such a large number of passwords can cause a major problem for users. It is, therefore, no surprise that users often select dictionary words or personal names as the basis for their passwords, as these are easier to remember. Having said this, only 15% of respondents felt that their passwords could be easily guessed. The phrasing of the question in this case gave examples of information that, if used as a basis for selection, could render the password more easily guessed (i.e. “is it part of your address, name, partner’s name?”). Although the majority of users considered themselves to be safe on this basis, the question did not provide an exhaustive list of what might constitute obvious choices. As such, many respondents may still have been using insecure passwords, such as dictionary words (which the aforementioned L0phtCrack tool can determine in less than a minute).

Not only do users often choose insecure passwords, they also frequently select the same password for multiple accounts, with 40% of respondents re-using the same password. As such, should an intruder gain access to one protected account, it is quite likely that he/she will be able to reuse that same password for other machines and applications. A further issue is that of the password’s lifetime. Once a password is illegitimately acquired then, without time limits, restricted logins or account monitoring, it is possible that the intruder would remain unnoticed until he/she committed an act that caused some form of disruption. The respondents were asked how frequently they changed their passwords and if they were forced to change their passwords by the system or the system administrators. As indicated in table 3, an alarming 34% of respondents claimed to never change their passwords. Furthermore, the responses to the subsequent question revealed that 51% were not forced to change their password by the system. The former represents bad practice on the part of the users, whereas the latter reflects poor system administration. From an administration



point of view, it is more encouraging to observe that 70% of users claimed to use systems in which a minimum password length is enforced. Having a minimum length of seven or more characters helps to ensure that passwords are more resilient to brute force attacks.

| Frequency of password change | Respondents |
|------------------------------|-------------|
| Weekly                       | 2%          |
| Fortnightly                  | 1%          |
| Monthly                      | 25%         |
| Six-monthly                  | 18%         |
| Less frequently              | 20%         |
| Never                        | 34%         |

**Table 3 : Frequency of password changes**

Responses to subsequent questions revealed that, in many cases, the respondents themselves were compromising password protection, with 15% admitting to writing them down and 29% willingly sharing them with colleagues. In addition to this, 31 (21%) of the 151 respondents who used computers at work claimed to have used another person’s password without their consent or knowledge.

These results serve to underline some of the known problems with passwords and provide the justification for the subsequent questions, which asked users about other forms of authentication.

**Alternative authentication and supervision methods**

One of the main objectives of the survey was to evaluate user’s opinions regarding different authentication methods. In order to achieve this, the respondents were asked to rate the acceptability of a variety of initial login and continuous supervision techniques on a 5-point sliding scale from ‘totally acceptable’ to ‘totally unacceptable’. A total of nine methods were cited, ranging from passwords to a variety of physiological and behavioural biometric methods. Each of the methods was briefly described on the questionnaire sheet to ensure that the respondents understood the context (using the text previously shown in table 1). Table 4 summarises the ranked results, which are also illustrated graphically in figure 2. The responses have been normalised to reflect the variable response rate to each question, as there was a higher response rate to questions on initial login authentication (probably reflecting a lack of understanding of the concept of continuous supervision amongst some respondents). The positive responses (‘totally acceptable’ and ‘acceptable’) were summed and then the total number of negative responses (‘unacceptable’ and ‘totally unacceptable’) were subtracted, thus producing a rank of user preference.

| Method               | Initial login authentication | Continuous supervision |
|----------------------|------------------------------|------------------------|
| Password             | 95.7%                        | -10.2%                 |
| Keystroke analysis   | 29.8%                        | 25.5%                  |
| Face recognition     | 49.1%                        | 3.2%                   |
| Mouse dynamics       | 21.3%                        | 21.8%                  |
| Voice verification   | 53.4%                        | -0.6%                  |
| Signature analysis   | 40.1%                        | -35.9%                 |
| Iris scanning        | 47.2%                        | -16.8%                 |
| Hand geometry        | 44.4%                        | -19.9%                 |
| Fingerprint analysis | 48.8%                        | -16.0%                 |

Table 4 : Ranked user preference of security methods

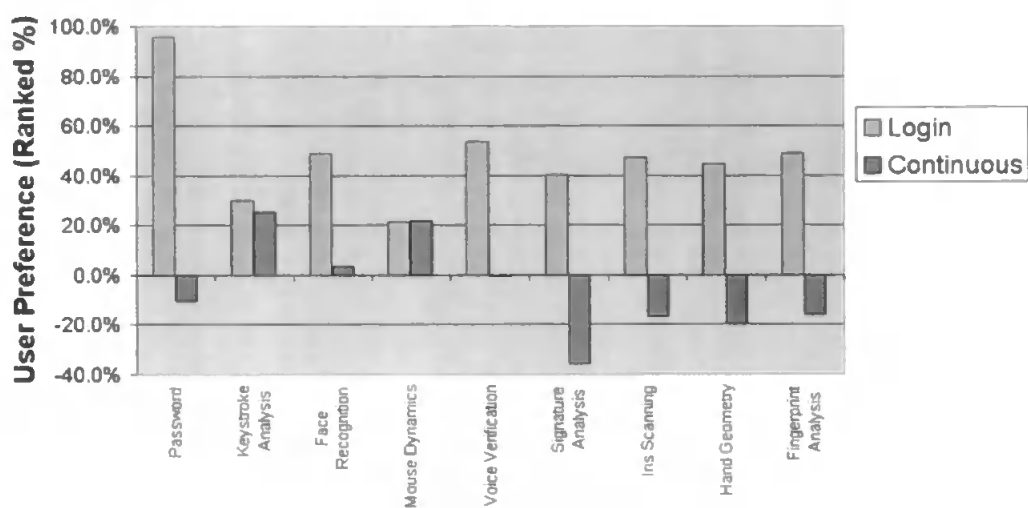


Figure 2 : User preference of authentication methods

As expected, the most popular form of initial login authentication was the password, with 90% of respondents rating it as ‘totally acceptable’ (scoring more than twice as many votes in this category than most other methods). However, this did not mean the outright rejection of alternative methods and many also achieved respectable scores. The authors were, however, surprised to see a general acceptance of mouse dynamics for initial login authentication. This was felt to be somewhat erroneous, as it is unlikely that moving the mouse for logging-on would provide sufficient data for a unique identification. It is expected that using a combination of methods, such as password and keystroke analysis, would provide a much more reliable method of initial login authentication.

It is clear that there is a high level of user acceptance for all the initial login authentication techniques suggested. Methods such as face recognition, voice verification, signature analysis, iris scanning, hand geometry and fingerprint analysis were all considered favourably. It is interesting to note that all of these techniques (with the exception of signature analysis) have had significant media coverage,

especially through film and television. It is possible that familiarity with these techniques influenced the respondents' choices. The acceptance of signature analysis cannot be readily explained by the familiarity with the technology through the media, however the concept of a signature as a means of identity verification is well established in our society.

After passwords, the most acceptable forms of login authentication were considered to be voice verification and fingerprint recognition, scoring raw overall acceptability ratings of 68% and 67% respectively. The latter result is somewhat surprising, in that conventional wisdom suggests that the association of fingerprints with criminal identification may represent a potential barrier to user acceptance. However, it is clear from these results that the majority of respondents are comfortable with the concept. It can, however, be noted that, in the normalised results (as presented in table 2), face recognition scored higher than fingerprints once negative responses had been taken into account

One of the significant questions posed in the survey was whether respondents would be comfortable with the concept of continuous supervision. This would provide a means for authentication to become an ongoing process within a logged in session, rather than being merely a one-time judgement at the beginning. This, in turn, would guard against situations such as an impostor replacing a legitimate user at the terminal or an impostor who may have been able to fool the initial login authentication system. In general, the respondents were positive towards the idea of monitoring, with 43% considering it acceptable, though 29% were unsure. However, the respondents considered only three techniques acceptable; namely keystroke analysis, mouse dynamics and face recognition (the latter being with a very low preference). Whilst the overall ranked results reflected sensible views, some of the individual responses in the underlying data did provide a few surprises. In particular, 34 respondents rated the use of signature analysis for continuous monitoring to be 'acceptable'. This is most likely to be a misunderstanding, as few computer users would be prepared to stop work and sign their name intermittently (a view borne out by the fact that 90 rated this as 'unacceptable').

Respondents were also asked to consider how long they would be prepared to spend creating a behaviour profile that the monitoring system would use to authenticate them. The responses are shown in table 5. It is clear that the majority of users would not be tolerant of explicit profiling activity for any long periods. Equally, the time that most of them would consider acceptable is 15 minutes or less – which would be unlikely to be adequate for some measures (e.g. whilst face and fingerprint recognition systems would allow adequate registration within this time, accurate measures relating to typing and more general system usage would require longer periods). As such, elements of profiling would need to occur as a transparent background task in order to ensure user acceptance.

| User-profile set-up time | Respondents |
|--------------------------|-------------|
| No time                  | 11%         |
| Up to 5 mins             | 36%         |
| Up to 15 mins            | 24%         |
| Up to 30 mins            | 13%         |
| Up to 1hr                | 12%         |
| > 1hr                    | 5%          |

**Table 5 : Acceptable duration of profiling activity**

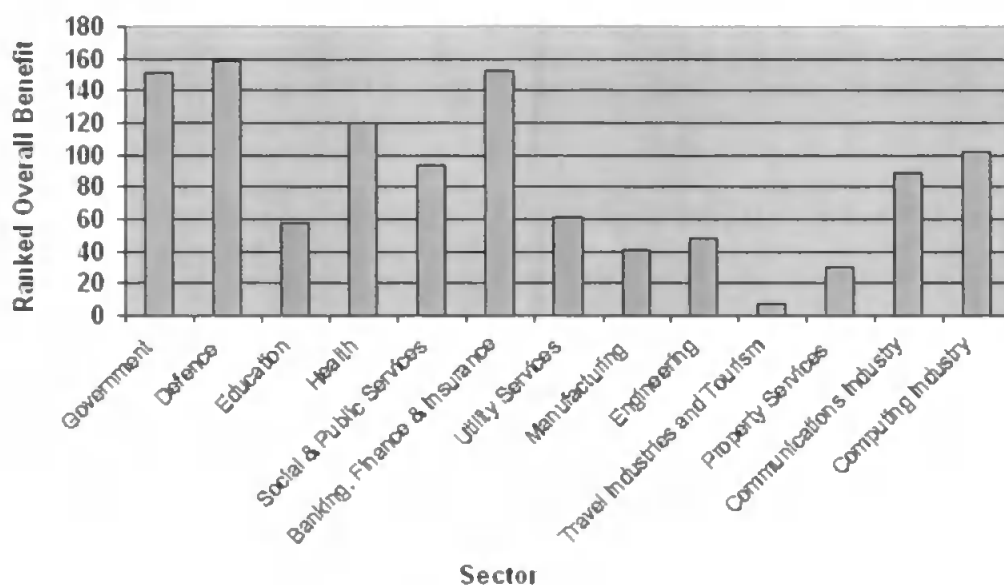
Once a profile has been created, there is still the possibility that a monitoring system may falsely reject a legitimate user, believing them to be an impostor. The questionnaire made the respondents aware of this and asked them how frequently they would be willing to tolerate such errors. The results are presented in table 6 and clearly illustrate that any deployed system would need to have a very low error rate in order to avoid alienating the user population.

| Frequency of false rejection | Respondents |
|------------------------------|-------------|
| Hourly                       | 7%          |
| Daily                        | 27%         |
| Weekly                       | 36%         |
| Never                        | 29%         |

**Table 6 : Perceived tolerable frequency of false rejection by monitoring system**

It is recognised that the concept of continuous supervision also introduces ethical considerations. Indeed, 40% stated that they would consider monitoring as an invasion of their privacy, with a further 18% being unsure. It is clear that if continuous supervision of users is to be implemented, then certain safeguards should be considered. In particular, users should be aware of the intended uses of the information collected. 45% of respondents felt that they could not trust their organisation to use the supervision data for security-related purposes only and were concerned that it could be utilised for an ulterior motive, such as monitoring work productivity. 85% stated that users should be aware of any monitoring being used. The simplest way to ensure these requirements are met is to involve the users in the planning and implementation of these systems and provide clear policies on the uses for the gathered information.

Finally, the respondents were asked to indicate which fields/sectors would benefit most from supervision of users by computer, rating the benefit from ‘great benefit’ to ‘no benefit at all’. These results were collated and ranked and are shown in figure 3.



**Figure 3 : Benefit from monitoring by sector**

As expected, the majority of respondents considered the areas of government, defence, health and banking to benefit most from user supervision (these being the areas with the most obviously sensitive systems and data to protect). However, the respondents felt that all areas could benefit from improved supervision, showing that there is still considerable concern over the perceived computer security across all sectors.

## Discussion

The results clearly demonstrate the shortcomings of password-based authentication, as well as the fact that, in spite of these, it remains the dominant form of user authentication. However, the fact that the respondents have shown a willingness to use alternative authentication techniques can be considered to be encouraging. It should be noted, however, that in the majority of cases, it is unlikely that the respondents had actually used the techniques that they were being asked to comment upon. As such, it is possible that their views may change if presented with the practical experience.

Given that a strong preference was expressed for passwords, consideration should be given to retaining them as the means of login authentication, whilst identifying means to compensate for their weaknesses. Suitable strategies in this respect could include:

- Utilising password login in conjunction with transparent keystroke analysis of the information entered. In this way, the user would be authenticated not only by *what* they type, but also *how* they type it. This should not have any significant influence on user acceptance, as the primary authentication mechanism will still appear to be the password.

- Retaining password-only authentication at login, but supplementing it with continuous supervision during the user session. The survey results suggest that techniques such as keystroke analysis and mouse dynamics would be acceptable to users in this regard.

The respondents preference for passwords is in agreement with the previously published results from the Australian TRUST project, which (from a survey of 76 participants) found users' principal preference to be for passwords, followed by physiological biometrics and, finally, behavioural measures [16]. The latter finding is, however, in contrast to the results from this study in that (for continuous monitoring) the behavioural techniques of keystroke and mouse dynamics were chosen in preference to the physiological technique of face recognition. Indeed, in the TRUST study, keystroke analysis and pointing device based verification scored the lowest of the seven biometrics assessed.

Although many considered the concept of continuous supervision to be acceptable for security purposes, the respondents showed concern over the potential wider use of such data. As such, it is important for organisations to establish agreed working practices to employees before proceeding with such methods (this may assist in reassuring those such as the 29% of respondents who were undecided over the acceptability of the monitoring concept). If such practices are not naturally adopted by organisations, it is possible (maybe even preferable in some cases) to legislate on acceptable supervision practices. This could be implemented in a similar way to that which restricts the rights of an employer to intercept and/or read an employee's email correspondence.

Overall, a significant factor in the acceptance of alternatives to the password will be that of education. If people can be shown that newer authentication techniques are safe, reliable and secure, then their acceptance is likely to be improved.

## Conclusions

The survey has shown that, although demonstrably weak, the password remains the most popular form of authentication in the minds of users. However, a number of other methods emerged as possible contenders and it is possible that practical experience of using them, combined with improved awareness of the vulnerabilities of passwords, would increase their perceived acceptability as alternatives.

Another conclusion that can be drawn from the survey results is that the use of continuous supervision is, in general, acceptable. However the viability of such a scheme would be dictated by the methods chosen and subject to suitable assurances being given to the monitored population regarding the planned uses of the collected data.

The findings from the survey will be used to inform on-going work in relation to an architecture for real-time user supervision and monitoring [17]. This system will be based upon composite authentication techniques, rather than attempting to apply particular techniques in isolation.

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# A conceptual intrusion monitoring architecture and thoughts on practical implementation

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## Abstract

The paper presents a conceptual description of the Intrusion Monitoring System (IMS) architecture, which is designed to facilitate detection of system penetration and other anomalous activity in a networked environment. The architecture is based upon eight functional elements, distributed between a monitoring host and a series of monitored client systems. The discussion also considers how the approach could be integrated within the Windows NT environment.

## 1 Introduction

The concept of real-time intrusion monitoring has been of interest in the IT security domain for a number of years, with the original idea having been proposed by Denning (1987). Such an approach is valuable as a means of combating a number of classes of system abuse, including penetration by unauthorised persons and misuse of privileges by registered users. In addition, abuse may be perpetrated by malicious software, such as viruses and Trojan Horse programs. Although a number of IDS have been developed (Mukherjee et al. 1994), these have generally targeted large systems or specific domains (e.g. military). Commercial implementations are generally restricted in their monitoring functionality. However, the increasing interconnection of corporate systems, coupled with reported increases in computer abuse incidents (CSI 1999), suggests that the use of more advanced intrusion monitoring functionality would be advantageous. This paper presents the conceptual architecture of the Intrusion Monitoring System (IMS), which aims to detect anomalous activity in a networked environment, followed by consideration of how to realise the approach in practice under Windows NT.

## 2 Intrusion Monitoring System overview

The IMS architecture was originally proposed by Furnell (1995) and is based upon the concept of a centralised *Host* handling the monitoring of one or more *Clients* on

local workstations. The Clients collect the required data relating to system activity and respond to any suspected intrusions detected by the Host. Monitoring is based upon the comparison of current activity against two categories of stored information, namely user behaviour profiles and generic intrusion rules. These approaches are common to other intrusion monitoring architectures, such as the Intrusion Detection Expert System described by Lunt (1990). User profiles could conceivably hold a range of identification, authentication and behavioural information relating to registered users. Examples of potential characteristics would include system access times and locations; typical levels of system resource utilisation; application and file usage; methods of user interaction; and biometrics (i.e. physiological and behavioural characteristics). Biometric monitoring is considered to be particularly appropriate to prevent impostor penetration and a number of options exist that could be employed in this context, including keystroke analysis, face recognition and voice recognition (Cope 1990). Other well-known biometrics, such as fingerprint recognition, are less strongly favoured in the IMS context, as less opportunity exists to integrate them in a manner that is transparent (and, hence, non-intrusive) to the legitimate user.

Some classes of intrusion or misuse can be trapped without identifying departures from historical patterns of user behaviour. The occurrence of some events will be suspicious in themselves and, therefore, the system requires a means to monitor for these as well. Examples of generic indicators would include consecutive access violations, out of hours access, account overuse / simultaneous access, use of inactive accounts and extensive use of help systems. While none of these alone would provide sufficient indication to state that an intrusion was in progress, the combination of two or more could be more persuasive. In the IMS context, these attack signatures would be represented via Intrusion Rules that, if satisfied, would increase the alert status of the system.

### 3 The IMS Architecture

**Anomaly Detector.** The *Anomaly Detector* analyses activity for suspected intrusions, comparing it against the behaviour profile of the current user's (claimed) identity, as well as against the generic intrusion rules. The detector is comprised of further sub-modules, each handling specific monitoring tasks (e.g. keystroke analysis, tracking of resource usage etc.). The detector maintains an *alert status table*, with entries existing throughout the life of each user-initiated session or process to indicate the level of detected anomalies and thereby the confidence of a potential intrusion. This information would be examined and updated each time activity data relating to the relevant user / process is analysed. The alert status level would increase in response to departures from the user-specific behaviour profile or the satisfaction of generic intrusion indicators. The level would be reduced after successful challenges or after a sufficient period of normal activity to allow the system to discount the previous anomaly. The alert status level can be linked with the types of activity that a subject is permitted to perform. In this way, a phased reduction of permitted behaviour would occur as the level increases. Sensitive activities / information could, therefore, be denied if doubt exists over the legitimacy of the current user, whilst still allowing more mundane activities to continue. The approach would demand that a maximum alert status threshold be associated with each of the activities or objects that IMS is to control.

**Profile Refiner.** User behaviour may legitimately alter over time. The *Profile Refiner* aims to provide an automatic means to account for such changes, using neural networks to analyse and recognise behavioural characteristics that might not be apparent to a human observer. In this way, the effectiveness of the system has the potential to improve over time. It might also be possible to determine which of the profiled characteristics provide the best discriminators for each user and thereby establish various levels of behavioural indicator (with the primary level representing the most reliable verifiers). This hierarchy could also be extended to allow for the fact that some characteristics may represent negative indicators (i.e. those that, despite refinement, are found to cause a high level of false rejection).

It would be undesirable for the *Profile Refiner* to utilise data that is later found to be anomalous. Refinement should, therefore, only take place after the termination of non-anomalous user sessions. User-specific profile records would also incorporate a series of flags to indicate whether the individual behaviour characteristics are ready to be used in supervision or still being

developed. This will allow a gradual training period to be defined for new user profiles without the IMS continually generating intrusion alerts (the flags would also allow a specific 'refinement only' period to be established for existing profiles that have proved to be inadequate for the legitimate user). The purpose of associating flags with each profile characteristic is so that some degree of monitoring could still continue whilst other aspects are being (re)trained.

**Recorder.** The *Recorder* handles the short-term storage of user-related activity data during a session and focuses specifically upon the collection of data relating to the profiled characteristics of a given user (e.g. collection of keystroke data in relation to the typing profile). Upon termination, the information will be used as input to the *Profile Refiner*, provided that the session was not considered anomalous. In the event of a proven anomaly, the *Recorder* can discard the session data.

**Archiver.** The *Archiver* collects data relating to *all* system activity and stores it in a long-term archive, providing a more permanent record of activities and suspected anomalies. The storage occurs regardless of whether sessions / processes are regarded as anomalous and details of all security relevant events are archived. Such events include login failures, intrusion alerts, authentication challenges and suspended sessions. However, in order to conserve storage space, it may be desirable to only record details of certain types of event. The *Archiver* is therefore configurable to suit the preferences of the organisation involved (note that the same would *not* be true for the *Recorder* as this would always need to collect information on any activities for which profile refinement may later occur). The long-term retention period of archived details would be organisation-dependent.

**Collector.** The *Collector* is responsible for obtaining information on all relevant client-side activity. The module must operate in such a way as to encompass, but be independent of, all system applications. It is envisaged that this could be best achieved by implementation at the operating system (OS) level, such that key events also lead to IMS notification. For example, a significant proportion of data collection could be based around the interception and redirection of selected OS service requests (such as file input / output, application execution, keyboard input). In some cases, data could be obtained directly from audit trail records – as in previous systems, such as Wisdom & Sense (Leipins and Vaccaro 1989.). However, with certain aspects (e.g. keystroke analysis) the required information will not be held by audit trails and implementation may, therefore, require a significant number of OS links.

Whilst this would serve to make this aspect of IMS very system specific, it would be more efficient than attempting to modify individual applications to provide relevant information to IMS.

**Responder.** This module resides in the Client and responds to anomalies detected by the Host. The operation centres around the continuous monitoring of the alert status transmitted by the Host, with increases in the level triggering appropriate actions. The nature of response at different levels would vary and a detailed discussion of the possible options is beyond the scope of this paper. However, appropriate responses might include: issuing of an explicit challenge for further authentication; recording of details in an intrusion log for later investigation; notification of the system manager; phased reduction of permitted behaviour; locking of the intruder's terminal; and termination of the anomalous session / process.

**Communicator.** The *Communicator* provides the network communications interface between the Host and the local Client(s). The principal functions include transmitting user and process information to the Host and then subsequently keeping the Client(s) informed of the current alert status. If implemented in a heterogeneous environment, the Client side would be responsible for resolving any operating system differences that exist within the monitoring domain, so that information could be presented to the Host in a consistent, standardised format. The actual communication could then be handled via a standard sockets approach, with protection provided by a technology such as Secure Sockets Layer (Frier et al. 1996).

**Controller.** This module allows the operation of the IMS system to be configured. On the Host side, this applies to the *Anomaly Detector* (e.g. behaviour characteristics to utilise, generic rules in operation), the *Profile Refiner* (e.g. frequency of refinement, acceptable thresholds for challenges) and the *Archiver* (e.g. level of detail required, specific events to record or exclude from logging). On the Client side, configuration relates to the *Collector* (e.g. the level of data collection, which could be automatically linked to the characteristics being monitored by the *Anomaly Detector*) and the *Responder* (e.g. the level of response required at each alert status level). These settings would be controlled and recorded through the Host system. Local Client(s) would then be configured at the time of session initiation. Other features would also be provided under the auspices of the *Controller*, including user profile management and update of the generic rulebase.

#### 4 IMS Implementation

Work is currently being conducted to develop an implementation for Windows NT. This requires replacement of the Graphical Identification and Authentication (GINA) Dynamic Link Library (DLL) - the interface through which a user can provide his/her identification, typically in the form of a username and password. However, it can be replaced with any desired authentication method (e.g. commercial products are available using fingerprint and faceprint methods). In addition to the GINA replacement, the IMS would also require software to provide the required continuous monitoring, together with a remote security server. The security server would be used to store, maintain and update the user profiles. This server would process all authentication requests together with local system audits and updates to profiles. This role is slightly different to that of a network server, which usually only authenticates requests for access at the beginning of a session. Instead, the security server would be responsible for ongoing authentication throughout a session. A user login would be performed locally (or remotely via a domain controller) and once the user's credentials are confirmed the monitoring program would be loaded to provide continuous user authentication. To prevent tampering, the IMS system would store user profiles remotely on the security server. These would be encrypted and downloaded at login (although for higher security the profiles could be maintained on the server with authentication requests being handled by the server). To ensure monitoring hardware has not been tampered with, a local machine audit can also be initiated together with checks for dependent entries in configuration files or registry keys.

To reduce network traffic, it is envisaged that the user authentication would be performed on the local computer with only warnings or profile updates being fed back to the security server. Under certain scenarios it may be necessary to lock local computers if contact is lost with the security server to ensure an intruder had not removed a computer. However, it should be noted that this creates a weak point and appropriate measures will be needed to prevent a single server stopping the entire network. This could take the form of a backup server, in a similar fashion to a secondary DNS server. Alternatively, the range of facilities available to the user can be restricted until they can be re-authenticated.

Once a user has been authenticated by the replacement GINA DLL, the IMS client would be activated. The IMS client would then check the IMS security server (host) for the users monitoring characteristics and rules, to allow it to select the most appropriate monitoring

programs. At this point, the selected characteristics would be loaded and initialised. To ensure ease of implementation and future modification, each distinct monitor program would be implemented as a system DLL. Taking the keystroke analysis example, the monitor program would install a system-wide hook to intercept all keystrokes received by the keyboard buffer and pass these to an analysis algorithm within the DLL. To ease the processing burden, the DLL would pass periodic samples of keystroke activity (either time or quantity based) to be analysed. The results of this analysis would then be passed on to the IMS client program to be either compared to the local copy of the user's profile or to be returned to the IMS Host for remote verification and subsequent action. In the event that the IMS detects a potential intruder, a call can be made to the GINA DLL to provide a request for further user authentication. (e.g. question and answer challenge or biometric identification request). As the GINA DLL provides the login interface for NT, it is impossible to perform a local user login without authenticating via the GINA DLL. This can be used to enforce a variety of security rules. For example, the system may refuse login without the presence of the IMS host, the system may only accept a user once a secondary authentication has been made or the system may disallow local logins if monitoring hardware (e.g. a camera) has been removed.

Under Windows NT, the *Anomaly Detector*, *Profile Refiner*, *Recorder* and *Archiver* would be implemented on the IMS Security server (Host) as a software suite. To facilitate future upgrades, each component would be contained within a separate DLL, with a front-end provided through a single executable. Depending on the size of the system being monitored, it may be necessary to distribute the tasks over multiple hosts to cope with the level of data analysis and profile updating. It may also be beneficial to implement these programs as services under NT – ensuring they are loaded at host boot-up. The *Collector* would be implemented as a mediator on the Client, collecting information via hooks that intercept system messages (e.g. keystrokes, mouse movements etc.) and forwarding this information on to the *Communicator*. This would again be held in a DLL, which would be called by the replacement GINA. The *Responder* would be implemented within the GINA DLL and provide a replacement login interface for NT. This would also interface to the *Communicator* and *Collector* for data acquisition and client-host communication. The *Communicator* provides the interface between the client and server IMS software. It would be implemented as a shared DLL (used by both client and host). The *Communicator* would use standard TCP/IP communication, with all data being encrypted using a standard algorithm. The *Controller* provides a

management interface to the IMS server software and would be implemented on the host as a single executable linking to the *Anomaly Detector*, *Profile Refiner*, *Recorder* and *Archiver* DLL's. Further details of the practical implementation approach can be found in Dowland and Furnell (2000).

## 5 Conclusions

Intrusion detection systems have the potential to provide an important contribution to system security, protecting against abuse by both external persons and organisational insiders. The IMS architecture represents an example approach and the paper has sought to describe the main functional elements. A system such as IMS is considered to represent a useful addition to Windows NT, which increasingly has a role in enterprise-level IT and, hence, an increasing requirement for strong protection. The paper has provided an indication of how IMS would be realised in the NT environment. The detailed mapping of the IMS approach to the NT architecture is currently in progress.

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# Enhancing Operating System Authentication Techniques

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## Abstract

The need for enhanced user authentication has been evident for some time; but has not been addressed at the operating system level to any degree. Whilst all mainstream operating systems offer some level of user identification and authentication, this is generally based on the username/password combination. Although a number of extensions to operating system security have been proposed (with some reaching implementation) none, as yet, have been integrated into the core operating system kernel. Although there are examples that extend the operating system security model with additional measures (e.g. plug-in fingerprint scanners), these merely extend the operating system security rather than replace it with a more secure version.

This paper will consider the need to improve operating system security focussing upon the enhancement of user identification and authentication. In particular, the security weaknesses of the Microsoft Windows NT environment will be considered, leading to a discussion of supervision techniques that may be integrated within the NT security model. Finally, the conceptual integration of an Intrusion Monitoring System (IMS) architecture is considered.

## Keywords

User authentication, user supervision, security, intrusion monitoring, Windows NT.

## Introduction

The most commonly used form of operating system user authentication is the username/password pair. In most systems, the allocation of passwords (and sometimes usernames) is entirely at the discretion of the users and, as such, is the cause of many security loopholes. The weaknesses of passwords as the primary form of user authentication have been documented in previous works (Jobusch and Oldehoeft, 1989; Cherry et al, 1992) and will not be covered in detail here. However, typical weaknesses include passwords being easily guessed, shared among users, the use of dictionary words (which are more vulnerable to attack) and being written down near PCs. Even when passwords are more selectively chosen, they are still vulnerable to brute force attack, especially with the fast processors and distributed password cracking software now freely available (Savill, 1999).

It is clear that the 'out of the box' configuration for an operating system is inadequate for most systems. For example, most UNIX installations leave many security 'back-doors' into the system wide open by default (e.g. default password settings that administrators *should* change, but often do not), which provide an easy target for hackers (Stoll, 1989). Similarly, a standard installation of Microsoft Windows NT requires many steps before it can be considered secure (Microsoft, 1999a). Relying on passwords in their common form is inadequate and, therefore, some form of advanced

user identification is desirable. Ideally, this should also be combined with some form of user monitoring; thus ensuring that a user's session cannot be hijacked. Hijacking occurs where a user's active session is taken over by another user (intruder). This can occur on a number of levels; firstly an intruder can simply resume a session by waiting for the user to leave their desk and then taking advantage of an unprotected computer. Alternatively, an intruder may connect a device (computer) to the target computer's network connection and masquerades as the target computer. Whilst hijacked sessions are most likely to occur in a corporate networked environment, there are still risks to SME's and individuals – this is especially true with the trend towards e-commerce and the increased confidence in purchasing on-line (NOP, 1999). An intruder may be able to capture a credit-card purchase and then either modify or replay that same exchange of data to their advantage. Enhancing user authentication is, therefore, of value to both the commercial and private sectors.

Another problem, which is often overlooked during the selection of appropriate security systems, is that of internal misuse of computer systems. Most systems rely on the username/password pair to identify and authenticate a user. Once this authentication has been given, the user is often free to access the system without further checks or monitoring. Whilst most systems offer the ability to selectively exclude users and/or groups from specific shared resources, this is not usually the default setting. For example, under Windows NT, shares are, by default, accessible to all users and an administrator must specifically set access rights to ensure a shared resource is protected from internal misuse. A similar issue relates to private use of computing resources. Although this is not usually considered to be a security risk, it can represent a loss to a business either through physical resource usage or loss of computer processing time. Often the biggest loss to a company is that of lost employee time; not just through the time lost by the employee concerned but also in the time taken to investigate the problem and prevent further misuse (Audit Commission, 1998).

## **Operating system security weaknesses**

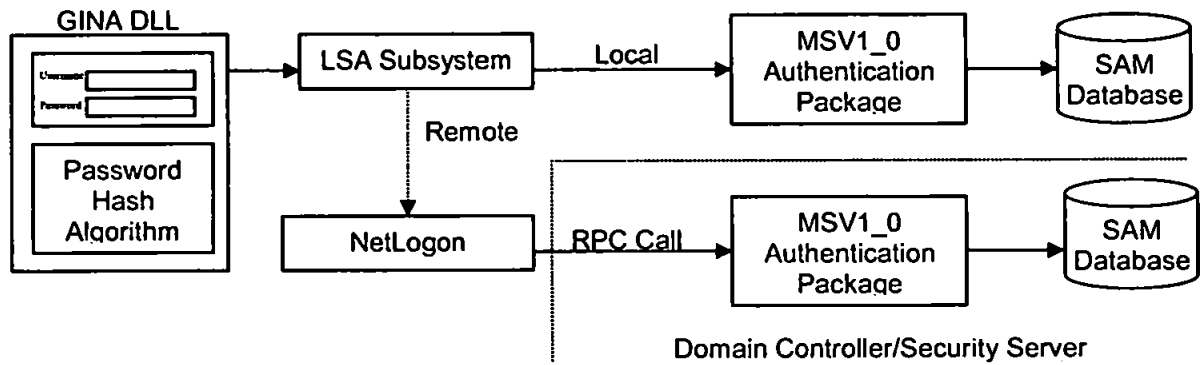
With operating systems such as Microsoft's Windows NT4 comprising several million lines of code, it is, perhaps, no surprise that security weaknesses should occur. However, it is often surprising to see the scope and frequency with which such fundamental flaws are found. Using Microsoft Windows NT4 as an example, the Microsoft Product Security Notification Service issues several warnings each week, each identifying a potential security problem with the operating system or its sub-components (Microsoft, 1999b). Of course, Microsoft Windows NT is not the only operating system to suffer with such security problems – the many flavours of Unix also generate hundreds of security patches each year (see <http://www.faqs.org/faqs/computer-security/most-common-qs/index.html>). However, the wider distribution of Windows means that the consequences of security vulnerabilities are potentially more wide reaching. A further drawback with a "popular" operating system is that as its popularity increases, it becomes a greater target to hackers partly due to the increased usage (and, therefore, potential targets) but also because of the greater availability of information relating to security weaknesses. This has been particularly prevalent with the appearance of "script-kiddies" (young inexperienced hackers), who frequently use the many resources (called "filez") which are available

from hacking sites on the Internet. A noticeable side effect of this is the use of alternative operating systems where security is of prime concern. For example, the US Army has switched to a MacOS-based web server platform, following a hacking incident when the server was running Windows NT (Donoghue, 1999). This is not to say that MacOS is any more secure than Windows NT, just less widely targeted.

Despite the frequency of these vulnerabilities, the only standard form of security provided by these operating systems for authentication purposes is the password.

### Enhancing Windows NT security

Windows NT security can be considered on two levels, local machine and domain or remote login (Figure 1).



**Figure 1 Local/remote user authentication**

When a local user presses the “Control-Alt-Del” combination to initiate a login they are prompted to enter their username/password pair. The NT hash algorithm is then applied to the password and is passed on to the Local Security Authority (LSA) which calls the MSV1\_0 authentication package. This hash is finally compared with the hash stored in the local Security Account Manager (SAM) database by the authentication package. Once a users’ password is authenticated, an access token is issued that is valid for that users’ session.

When a user wishes to be authenticated across a network (to log-in to a domain controller or for access to a remote machine), the password hash must be transferred across the network. When the user is prompted for their username/password they are also required to enter a valid domain. When the authentication package identifies that the account is not held locally, a call is made to the NetLogon service which sets-up a secure Remote Procedure Call (RPC) session to the domain controller to authenticate the login. The domain controller then issues a 16-bit challenge (the nonce). This challenge is then encrypted together with the password hash and is returned to the domain controller for authentication. Finally, the domain controller returns an access token which is valid for that users’ session.

One of the main problems of the above technique is that once the challenge (nonce) has been intercepted and with knowledge of the encryption algorithm it is possible to

determine the password hash. Given a known hash, it is feasible (with today's technology) to guess (using a dictionary and/or brute-force attack) the original password.

To achieve a more comprehensive approach under Windows NT would require a replacement GINA Graphical Identification aNd Authentication DLL (core user login system library e.g. username/password prompt). The GINA DLL provides an interface through which a user can provide his/her identification. This typically takes the form of the traditional username/password, but can be replaced with any form of identification (e.g. fingerprint scanner, iris scanner etc.).

There are a number of "add-on" software/hardware packages that can be used to enhance Windows NT security. One of the most common packages currently available is the fingerprint scanner. This is a small device that connects to the PC and provides a cost-effective way of authenticating a login attempt. These devices typically provide an additional security module that integrates into the NT security model. Similar devices are also available to capture handprint geometry, facial patterns and there are devices appearing that are capable of iris scanning. Although these packages allow the enhancement of NT security by removing the need for the user to remember a password, they are not completely integrated into the operating system and only provide a replacement for the username/password prompt. There is also a significant cost overhead to be considered (for example, a fingerprint based authentication system would require the purchase of sufficient scanners for all the PC's in an organisation). Many of these solutions also depend on additional hardware that is dedicated to the task of providing enhanced authentication and, therefore, provides no additional benefit to the organisation concerned (i.e. no purpose other than security).

Even if these techniques were integrated into the NT security model, there are still gaps which leave significant security weaknesses. For example, even with a fingerprint scanner, once the user has logged-in using their finger, there is no guarantee that the same user will sit down and continue with the session. Similarly, if a user leaves their workstation, there is no means of checking if the user who continues the session is the same that started it. (Although all versions of Windows allow the configuration of a screensaver with password protection, this is not set by default. It should also be noted that the computer is unprotected from the time the user leaves their desk to the point at which the screensaver is activated, unless they explicitly lock the terminal). Due to these risks, some form of ongoing user supervision is required to ensure that the current user is the same as the user who activated the session. The remainder of this paper considers the adoption of an Intrusion Monitoring System (IMS) and the technical aspects involved in integrating into the Windows NT security model.

## **Description of an IMS**

Following previous research work, a proposed IMS architecture is shown in figure 2. The specific functionality of this architecture has been described in a previous paper and will not be described in detail here (Furnell et al, 1997). At the basic level, the approach involves an IMS host monitoring activity occurring on a series of client systems. The client/server relationship of the IMS architecture shown fits neatly into the Windows



NT security model architecture and the proposed IMS integration is described later in this paper. Further research work is necessary to fully integrate the IMS architecture into the Windows NT security model and will be the subject of a later paper.

The **Anomaly Detector** analyses the data gathered by the IMS client for signs of suspected intrusion. This data can be compared against both the user's behaviour profile and the generic intrusion rules (i.e. attack signatures).

The **Profile Refiner** allows the automatic modification of a user's profile in response to a valid session profile. This recognises the fact that a user's behaviour pattern may change over time (e.g. in a scenario where typing style has been profiled, their typing skill may improve) and allows a user's profile to evolve. Due to the nature of the data and the difficulty in recognising gradual behavioural pattern changes, it is likely that this would be implemented using some form of neural network (Furnell, 1994).

The **Recorder** stores a temporary record of system and user activity during a session (session profile) which can be used by the Profile Refiner to update the user profile, providing the session was not considered anomalous.

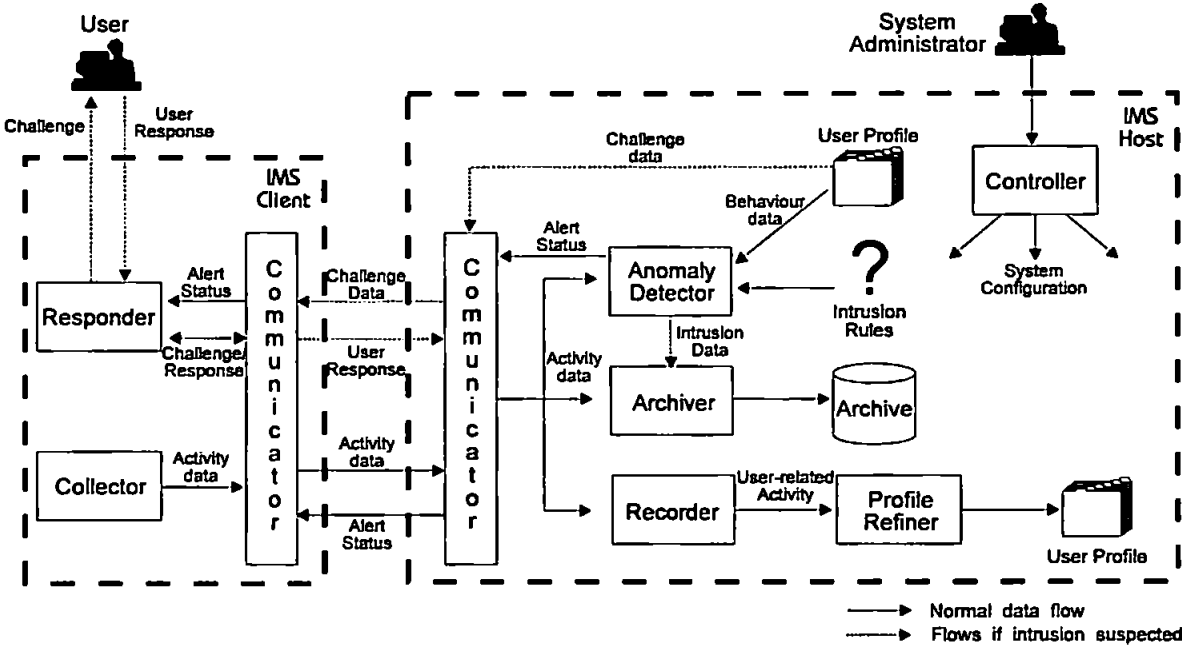


Figure 2 Proposed IMS Architecture

The **Archiver** provides an audit log, storing all security relevant events. This could also be extended to monitor *all* events if an organisation requires a more detailed log of user activity (e.g. to monitor user performance).

The **Collector** provides an interface between the IMS client and the applications running on the client computer. The collector is responsible for gathering information relevant to the user and his/her system activities. Under Windows NT the collector would be implemented as a mediator, collecting information gathered by low-level

system functions that intercept system messages (e.g. keystrokes, mouse movements etc.) and forwarding this information on to the communicator.

The **Responder** provides user interface between the IMS software suite and the end-user. Its main task is that of monitoring the signals send from the server to the client and taking appropriate action where necessary. Possible actions include; issuing a user authentication challenge, suspending a session, limiting a user's actions or cancelling a process.

The **Communicator** provides the interface between the client and server IMS software. The communicator is responsible for ensuring a consistent, reliable and secure exchange of data between the client and server. Where an IMS system is implemented in a heterogeneous environment, the communicator is also responsible for data translation to provide consistent data formatting between different client platforms.

The **Controller** provides a management interface to the IMS server software allowing an administrator to configure the IMS system-operating parameters. The controller also allows an administrator to configure client-monitoring characteristics on a global, group, machine or individual user basis.

An Intrusion Monitoring System incorporates identification and authentication of users, monitoring of users for unusual behaviour or characteristics, together with the ability to modify the profile of a user to reflect changing patterns of use/behaviour. An IMS can rely on many physiological characteristics of the user (e.g fingerprint, voice etc.) and can also monitor behavioural traits such as keystroke patterns, mouse dynamics and application/resource usage. However, it should be noted that the majority of commercially available IMS systems rely on traditional methods of user authentication

A strong potential candidate for a monitoring characteristic is that of keystroke analysis. This is a particularly attractive characteristic, as it requires no additional hardware (cost) or proprietary drivers (development time). By monitoring a user's typing profile it is possible to determine, with some accuracy, the identity of the current user. The use of a users' typing pattern as an authentication characteristic has been described in a number of papers (Furnell et al, 1996; Brown and Rogers, 1993) and has shown to be a strong distinguishing factor in certain contexts with overall False Acceptance Rate (FAR) figures as low as 4.2% being observed.

Although keystroke analysis is a good characteristic upon which to base user authentication, there are limitations. One of the major drawbacks of this characteristic is the very fact that users have a broad range of typing patterns. An inexperienced typist will use a keyboard in a slow deliberate manner, having a slow typing rate and most probably a high error rate. A trained touch-typist will type quickly with a low error rate. However, most inexperienced typists will type equally slowly and most touch-typists will type equally quickly. It is quite possible that the inter-keystroke time will be such that two typists may be indistinguishable in normal working environments.

Keystroke analysis may also be inappropriate depending on the environment in which it is used. For example, if a user is typing in numeric data for a prolonged period, it may

be impossible to achieve a statistically valid sample of keystroke data upon which to base the authentication judgement. Similarly, if a user were drawing with a mouse, there would be no keystrokes to analyse.

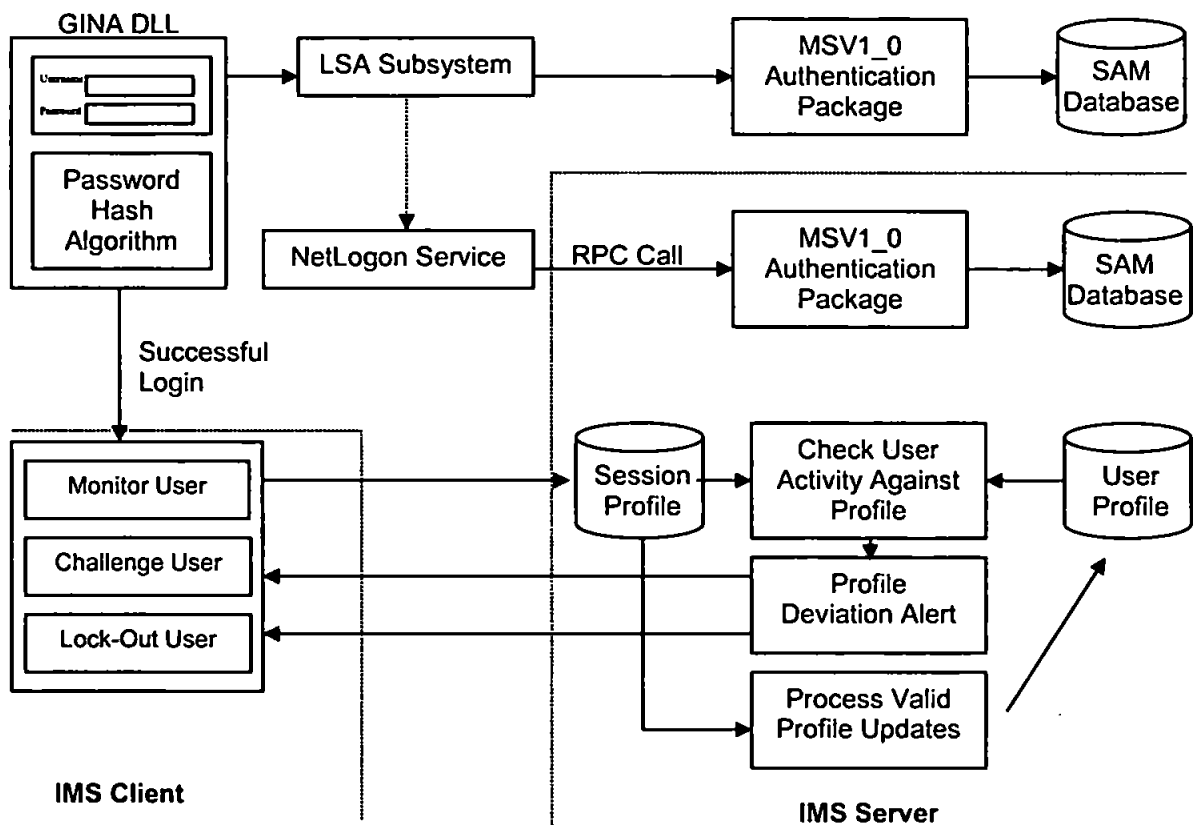
From this, we can see that a composite approach is needed, where several appropriate authentication and monitoring techniques are applied. For example, a user may be initially authenticated by their fingerprint, after which their typing profile and application usage can be monitored. Similarly, if that user then starts to draw using the mouse, data can be recorded to determine if the dynamic movement of the mouse is consistent with the users' profile. This technique can also be applied where users *hotdesk*. If a user moves to a desk with an additional security-relevant device (e.g. a camera for faceprint recognition), the additional measures can be detected during an audit and then utilised for that user depending upon the settings in their profile.

## **Integrating an IMS into the Windows NT security model**

If we consider the concept of an IMS, the username/password pair could be used to identify the user with a partial degree of certainty, whilst the continuously evaluated characteristics would allow the user to be monitored throughout the session. Using the previous example of keystroke analysis, a users' typing pattern can be monitored throughout the active session and compared with a historical profile. Deviation from this profile can be flagged and a threshold set beyond which further authentication of the user would be required (Furnell, 1995). This trust level can also determine the frequency of monitoring and, where further authentication is considered necessary, the degree of certainty needed (and, hence, the form of authentication to request).

To achieve an Intrusion Monitoring System (IMS) under Windows NT would require a replacement GINA DLL and an additional piece of software to provide the required continuous monitoring together with a remote security server. A security server (or some form of centralised system) would be used to store, maintain and update the user profiles. This server would (in an ideal system) process all authentication requests together with local system audits and updates to profiles. This role is slightly different to that of a network server, which, usually, only authenticates requests for access at the beginning of a session. Instead, the security server would be responsible for ongoing authentication of a user throughout a session.

A user login would be performed locally (or remotely via a domain controller) and once the user's credentials are confirmed the monitoring program would be loaded to provide continuous user authentication (Figure 3). To prevent tampering, the IMS system would store user profiles remotely on a security server. The profiles would be encrypted and downloaded at login to the local computer (although for higher security the profiles could be maintained on the server, with authentication requests being handled by the server). To also offer security for the hardware (to ensure monitoring hardware had not been removed) a local machine audit can also be initiated, together with checks for dependent entries in configuration files or registry keys. An IMS system would also allow updating of the user profiles, to take into consideration changing user behaviour (e.g. keystroke patterns, application usage etc.) or appearance (e.g. facial recognition).



**Figure 3 Prototype IMS-NT Integration**

To reduce network traffic, it is envisaged that the user authentication would be performed on the local computer with only warnings or profile updates being fed back to the security server. Under certain scenarios it may be necessary to lock local computers if contact is lost with the security server to ensure an intruder had not removed a computer. However, it should be noted that this creates a weak point and appropriate measures will be needed to prevent a single server stopping the entire network, this could take the form of a backup server (in a similar fashion to a secondary DNS server in an Internet context). Alternatively, the range of facilities available to the user can be restricted until the user can be re-authenticated. Another possible weak-point is the profile update process. It is important that the profile update is only performed once a user authentication confidence level is exceeded and it is established that the computer concerned has not been tampered with. In the event that a users' authentication threshold has been uncertain and/or the computer may have been tampered with, any proposed changes to the user profile should be discarded.

One of the most important factors in the implementation of continuous user monitoring is ensuring the transparency of the monitoring process. A system that requires users to continuously re-authenticate themselves will not be successful. Therefore, an IMS should allow background monitoring of an authenticated user, only interrupting the user in the event that further authentication is necessary (e.g. in the form of a challenge-response question).

Clearly an IMS system can provide enhanced user authentication. However, there is no single system configuration that will meet all the needs of all the users. Instead configuration of the security server and client monitoring software is dependent on the level of security required by the organisation and amount of inconvenience that is tolerable to the users (the classic False Acceptance Rate versus False Rejection Rate dichotomy) (Cope, 1990).

## Conclusions

As the need for enhanced user authentication grows, operating systems will be extended to provide the necessary services. Windows NT already allows the use of a replacement GINA DLL, which allows OEM security vendors to supplement the Windows NT username/password login with additional/replacement authentication techniques. Alternative login techniques (e.g. fingerprint identification) allow the system confidence in user validity to be increased, but further security is needed to ensure the continued confidence in the user once past the initial login process. A process of continuous user authentication and monitoring, as described in the paper, is therefore desirable.

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# A conceptual architecture for real-time intrusion monitoring

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## Keywords

Information technology, Access control, Monitoring, User studies, Computer security

## Abstract

The detection and prevention of authorised activities, by both external parties and internal personnel, is an important issue within IT systems. Traditional methods of user authentication and access control do not provide comprehensive protection and offer opportunities for compromise by various classes of abuser. A potential solution is provided in the form of intrusion detection systems, which are able to provide proactive monitoring of system activity and apply automatic responses in the event of suspected problems. This paper presents the principles of intrusion monitoring and then proceeds to describe the conceptual architecture of the Intrusion Monitoring System (IMS), an approach that is the focus of current research and development by the authors. The main functional elements of the IMS architecture are described, followed by thoughts regarding the practical implementation and the associated advantages (and potential disadvantages) that this would deliver. It is concluded that whilst an IMS-type approach would not represent a total replacement for conventional controls, it would represent an effective means to complement the protection already provided.

## Introduction

In typical IT systems, protection against unauthorised user activities is usually provided via login authentication and access controls. The majority of authentication schemes are based upon traditional password methods. The weaknesses of passwords are well-known (Jobusch and Oldehoeft, 1989), but their simplicity (from both user and developer perspectives) serves to ensure their continued use. A significant issue with passwords is that they typically provide a one-off authentication judgement at the beginning of a user session. From that point, protection against unauthorised user activity is reliant upon access controls applied to specific data and resources. Whilst these can be utilised in an effective manner, they are themselves reliant upon appropriate system administration to grant suitable access rights and privileges to users. However, depending upon the level of control imposed, this scenario still offers the potential for unauthorised activity. The normal means of monitoring and identifying this is via audit trails, which maintain a record of nominated security-relevant activities within the system and can be inspected at a later time in order to identify anomalies. The problem with this approach is that any detection of unauthorised activity will be retrospective, when significant damage may already have been done. In addition, previous research findings suggest that while many organisations may maintain audit trail information, only a small percentage (10 per cent) of them actively follow up the information collected (Gliss, 1990). As such, breaches of security may potentially remain unnoticed for some time. What is, therefore, required is an automated, proactive means of detecting and responding to unauthorised

access/activity. Such a solution is provided by intrusion detection systems.

The concept of intrusion detection can be traced to original work by Denning (1987), who proposed a model for an intrusion detection system (IDS). This work led to a number of practical IDS implementations from various organisations, in particular the IDES system from SRI (Lunt, 1990). Indeed, intrusion monitoring is still an area of active research[1], indicating that the overall issue has yet to be resolved.

This paper presents an approach to guard against these classes of intrusion and misuse, in the form of the Intrusion Monitoring System (IMS) architecture. The discussion begins by presenting the principles that underlie the intrusion monitoring process, followed by a conceptual description of the IMS architecture. The paper then proceeds to examine a number of issues relating to practical implementation aspects.

## Principles of intrusion monitoring

This section presents a number of general principles that underlie the concept of intrusion monitoring and detection, which will enable the architectural approach proposed by IMS to be more fully understood and appreciated.

### Categorising system intrusions and misuse

At the highest level, intrusions or misuse will be the result of actions by users or processes, which will operate on one or more targets (which may include data (files), system devices and other users or processes). The purpose of introducing supervision will be two-fold:

- 1 to ensure that systems are only accessed by authorised users;
- 2 to ensure that systems are only used for authorised purposes.

User actions can be categorised as being either legitimate or illegitimate. However, it



is useful if a more detailed breakdown than this can be derived for the different potential classes of illegitimate activity. For example, all of the following scenarios represent types of illegitimate activity that should be monitored:

- an illegitimate action that is still within the normal authorisation of a valid user (i.e. abuse of privileges);
- an action by a valid user which is outside the normal limits of authorisation; and
- any action by an unauthorised user.

In addition, it is necessary to recognise differences in the types of potential system abuser. These have already been comprehensively categorised by Anderson (1980), and are described in Table I.

These groupings are considered appropriate for describing the different types of user-related abuse within an intrusion monitoring framework and will, therefore, be adopted for the remainder of the discussion. Whilst it is also possible to develop a deeper profile of potential intruders, by considering factors such as the common motivations behind abuse (e.g. money, ideology, egotism etc.), these are not explored here as knowledge of them would not contribute to the process of detection.

It should be noted that Anderson's categorisations do not take into account any of the categories of abuse that may result from software activity (e.g. viruses, Trojan Horses etc.). This is understandable given that the analysis was made in 1980 before such incidents had become commonplace. However, there has been a significant increase in such attacks over the last decade and evidence suggests that viruses are now the major cause of security breaches in both networked and standalone PC systems (National Computing Centre, 1998). It is now extremely unlikely that the problem will ever disappear and, therefore, countering such activity should also be within the scope of a comprehensive monitor. As a consequence, a further category of intrusion, called

malicious process (or malware), can be added to Anderson's list. These may introduce various undesirable consequences, including the alteration or destruction of data, creation of false data, degradation of system performance, crashing of systems or other effects that might render data or systems inaccessible (Brunnstein *et al.* 1990).

**Monitoring and detecting intrusions**

The supervision of activities (and resulting anomaly detection) can be based upon user behaviour profiles and generic intrusion indicators. These approaches are common to other intrusion monitoring architectures, such as the IDES system mentioned earlier.

User profiles could conceivably hold a range of identification, authentication and behavioural information relating to registered users. Examples of potential profiled characteristics would include:

- system access times and locations;
- typical levels of system resource utilisation;
- application and file usage;
- methods of user interaction (e.g. GUI versus command line), and
- biometric information (encompassing both physiological and behavioural characteristics).

The use of biometric monitoring is considered to be particularly appropriate to prevent impostor penetration and masquerade attacks. A number of options exist that could be employed in this context, including keystroke analysis (i.e. monitoring of the current user's typing style), face recognition and voice recognition (Miller, 1994).

It is also recognised that some classes of intrusion or misuse can be trapped without identifying departures from historical patterns of user behaviour. As such, generic intrusion rules (also known as attack signatures) may be utilised to identify the occurrence of events that are suspicious in themselves (i.e. irrespective of the user involved). Examples of such generic indicators would include the following:

- consecutive access violations;
- out of hours access;
- account overuse/simultaneous access;
- use of inactive accounts;
- copying of password file;
- extensive use of help systems; and
- modification of an executable file.

While none of these alone would provide sufficient indication to state that an intrusion was in progress, the combination of two or more could be considered more persuasive. In the IMS context, the

**Table I**  
Categories of system abuser

| Abuser type          | Description                                                                                                                 |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------|
| External penetrators | Outsiders attempting to gain unauthorised access to the system                                                              |
| Internal penetrators | Authorised users of the system who access data, resources or programs to which they are not entitled. Sub-categorised into: |
|                      | <i>Masqueraders</i> Users who operate under the identity of another user                                                    |
|                      | <i>Clandestine users</i> Users who evade access controls and auditing                                                       |
| Misfeasors           | Users who are authorised to use the system and resources accessed, but misuse their privileges                              |



occurrence of any such events would increase the alert status of the system (which, as discussed later, could result in a range of potential responses as different threshold values were reached).

A full IMS would operate by comparing current system activity against information held in a knowledge base. The knowledge base would effectively maintain two models of activity for reference by IMS:

- 1 normal activity (i.e. the user behavioural profiles); and
- 2 intrusive activity (i.e. the generic rules).

These models will determine what types of activities and events the system will look for and, as such, an event will be judged to be indicative of a suspected intrusion if:

- it is compatible with intrusive activity OR
- it is incompatible with normal activity.

Having considered these principles, the proposed architecture for a practical monitoring system can now be presented.

### **Intrusion monitoring system architecture**

At a high level, the IMS architecture is based upon the concept of a centralised host handling the monitoring and supervision of one or more networked clients running on local workstations. The purpose of the clients is to collect the required data relating to user and process activity and respond to any suspected intrusions detected by the host.

All behaviour profiles, generic rules and such like are maintained securely at the host, which also handles all of the analysis and the main bulk of other processing associated with the supervision. By contrast, the client involves no local data storage and acts almost exclusively as an agent of the host.

At a lower level, the host and client systems will be comprised of a number of modules, each handling a different aspect of the overall intrusion monitoring task, as illustrated in Figure 1. The modules shown are intended to represent the conceptual elements of the system, but could also equate to the coded functional elements in a full implementation. The key aspects of this design are defined in the sections that follow.

#### **Anomaly detector**

The *anomaly detector* analyses user and process activity for signs of suspected intrusion, comparing it against the behaviour profiles (class and user-specific) that apply to the current user's (claimed) identity as well as against the generic intrusion rules. In practice, this module will

be comprised of a number of further sub-modules, each handling a specific aspect of anomaly detection and behaviour monitoring (e.g. keystroke analysis).

The detector maintains an *alert status table*, with entries existing throughout the life of each user-initiated session or process to indicate the level of detected anomalies and thereby the confidence of a potential intrusion. Each entry contains the basic information shown in Table II, which is examined and updated each time activity data relating to the relevant user/process analysed.

It is envisaged that, at its most basic, the "alert status level" could be a simple aggregate value based on the number of behavioural anomalies detected and intrusion rules satisfied (with the monitored characteristics and rules having been weighted to indicate their significance). The entry relating to "idle time" will be used to allow the phased reduction of the alert status level after certain periods of inactivity. Recording a tally of previous challenges would then be used as a safeguard to determine whether the level of IMS response should be escalated in response to an anomaly even if the alert status is currently low (i.e. as a result of the phased reduction). As Table II illustrates, the alert status table might also be used to store other information, such as the time of session/process initiation or the number of access violations incurred. These would be used for the purposes of on-going comparison against behaviour profiles (for example, session start time could be used to derive the current session length) and would also be required to be maintained throughout the life of the session. It should be noted that some of the table entries are most applicable in the context of monitoring user sessions and will be redundant in the case of process supervision.

The alert status level would increase in response to both departures from a user's historical behaviour profile and the satisfaction of generic intrusion indicators. Under normal circumstances, the detector would commence supervision of a session with an alert status of zero (i.e. no suspicion of an intrusion). However, factors such as failed login attempts, system configuration anomalies and the like could cause it to begin with a non-zero status so that it is essentially more sensitive to further anomalies in the initial instance. The alert status would be reduced after successful challenges or after a sufficient period of normal activity to allow the system to discount the previous anomaly.

Figure 1  
IMS architecture

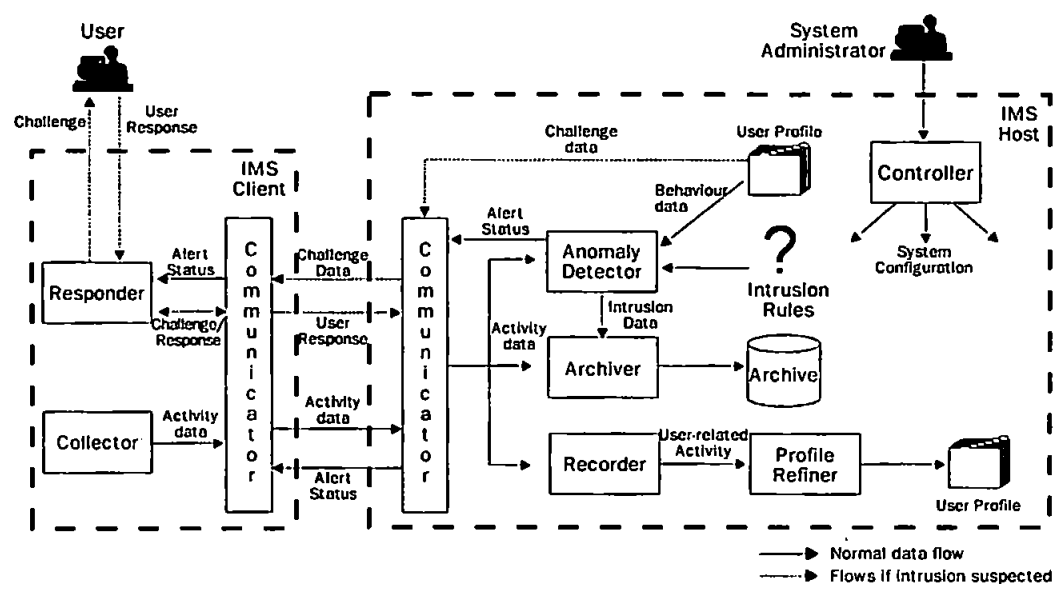


Table II  
Structure of alert status table entry

| User/process ID | Alert status level | Idle time | # previous challenges | Session start | # access violations |
|-----------------|--------------------|-----------|-----------------------|---------------|---------------------|
|-----------------|--------------------|-----------|-----------------------|---------------|---------------------|

Profile refiner

It is desirable for IMS to utilise user-related activity data in two ways – to analyse for anomaly detection and as the basis for updating behaviour profiles. This second point recognises the possibility that user behaviour may legitimately alter over time (e.g. as a result of access to new applications, improvements in typing ability etc.). The purpose of the *profile refiner* would, therefore, be to provide an automatic means for user-specific profiles to be updated to account for such changes.

It would be most appropriate for the *profile refiner* to be based upon a neural network approach (Bishop, 1995), given that the inherent ability to analyse and recognise patterns could allow behavioural characteristics to be identified that might not be apparent to a human observer. In this way, the effectiveness of the system would have the potential to improve over time, in that it could gradually learn more patterns of legitimate activity for each user (building upon the foundation provided by the generic rules and the initial profiles). It might also be possible to determine which of the profiled characteristics provide the best discriminators for each user and thereby establish (for example) primary, secondary and tertiary level behaviour indicators (with

the primary level representing the most reliable identity verifiers). This hierarchy could also be extended to allow for the fact that some characteristics may represent negative indicators (i.e. those that, despite refinement, are found to cause a high level of false alarms).

It would be undesirable for the *profile refiner* to utilise data that is later found to be anomalous. Refinement should, therefore, only take place after the termination of user sessions (provided, of course, that no intrusions were proven during this time). However, it is also considered sensible to allow refinement to proceed if any challenges that were generated were correctly answered by the user (the reason being that the generation of the alert may be indicative that legitimate behaviour has departed from the profile and that refinement is, therefore, necessary). However, in order to help guard against the recognised problem that misfeasors will answer challenges correctly, refinement should be performed on the proviso that the number of alerts raised is small relative to the length of the session (i.e. two alerts in a three hour session would be acceptable, whereas the same number in a ten minute session would be very suspicious). Additionally, any activity occurring during periods where supervision

of the relevant aspect is suspended cannot reliably be used for profile refinement.

User-specific profile records would also incorporate a series of flags to indicate whether the individual behaviour characteristics are ready to be used in supervision or still being developed. This will allow a gradual training period to be defined for new user profiles without the IMS continually generating intrusion alerts (the flags would also allow a specific refinement only period to be established for existing profiles that have proved to be inadequate for the legitimate user). The purpose of associating flags with each profile characteristic is so that some degree of monitoring could still continue whilst other aspects are being (re)trained. The flags could also be used to allow the total disablement of some aspects of monitoring if, for example, some characteristics are found to be inappropriate to certain users.

Data relating to process activity would not be used for refinement as the generic rulebase would remain static (unless specific information on new intrusion methods is introduced by the system administrator).

#### Recorder

The *recorder* handles the short-term storage of user-related activity data during the period of a user session and focuses specifically upon the collection of data relating to the profiled characteristics of a given user (e.g. collection of keystroke data in relation to the typing profile). Upon termination, the information will be used as input to the *profile refiner*, provided that the session was not considered anomalous. In the event of a proven anomaly, the *recorder* can discard its stored information for the session.

#### Archiver

The *archiver* collects data relating to all system activity and stores it in a long-term archive (in the same manner as a traditional audit trail), providing a more permanent record of activities and suspected anomalies. The storage will occur regardless of whether sessions/processes are regarded as anomalous and details of all security relevant events will be archived. Such events will include login failures, intrusion alerts, authentication challenges, suspended sessions and the like. The basic format of the archive records would be as shown in Table III.

However, in order to conserve storage space, it may be desirable in some scenarios to only record details of certain types of event. The *archiver* would, therefore, be configurable to suit the preferences of the establishment involved (note that the same would not necessarily be true for the *recorder* as this would always need to collect information on any activities for which profile refinement may later occur). The long-term retention period of archived details would be determined by the security policy of the organisation involved.

#### Collector

The *collector* represents the interface between the IMS and the existing information system/applications, with the responsibility for obtaining information on all relevant user and system activity. The module would be required to operate in such a way as to encompass, but be independent of, all system applications. It is envisaged that this could be best achieved by implementation at the operating system (OS) level, such that key events also lead to IMS notification. For example, a significant proportion of data collection could be based around the interception and redirection of selected OS interrupts and service requests (such as file input/output, application execution, keyboard input). These would be monitored with two objectives:

- 1 to collect data on those events which pertain to monitored behaviour characteristics; and
- 2 to identify those events which may affect the security of the system (for comparison against generic intrusion indicators).

In some cases, the required data could be obtained directly from existing audit trail records on the underlying system. However, with certain aspects (e.g. keystroke analysis) the required information will not be maintained in audit trails and implementation may, therefore, require a significant number of operating system links. Whilst this would serve to make this aspect of IMS very system specific, it would be considerably more efficient than attempting to modify each individual application to specifically provide relevant information to IMS. The system specific coding of the *collector* would only need to be done once, whereas modifications would be required to all current and future applications (which would be likely to be a non-trivial

Table III  
IMS archive record structure

| Date | Time | User/process ID | Logged event | Privileges | Resources utilised |
|------|------|-----------------|--------------|------------|--------------------|
|------|------|-----------------|--------------|------------|--------------------|

undertaking and potentially impossible in the case of commercial packages where the source code may be unobtainable).

As with the configuration of the *archiver*, the resolution of data collection would be determined at the host by the system administrator.

### **Responder**

This module resides in the IMS client and handles the task of responding to anomalies detected by the host. The operation of the *responder* would centre around the continuous monitoring of the alert status transmitted by the host, with increases in the level triggering appropriate actions. The nature of the response might include the issue of a user authentication challenge, suspension of a session or cancellation of a process. The issue of appropriate response is discussed in more detail later in the paper.

In some implementation scenarios, the *responder* might also be responsible for handling the initial user identification and authentication process that is required to gain access to the system in the first instance.

### **Communicator**

The *communicator* provides the network communications interface between the host and the client(s) operating on the local systems. As such, the functionality of this module is duplicated on both sides of the link. The principal functions would include transmitting user and process information to the host and then subsequently keeping the client(s) informed of the current alert status. If implemented in a heterogeneous environment, the client side of the module would be responsible for resolving any operating system differences that exist within the monitoring domain so that information could be presented to the host in a consistent, standardised format.

### **Controller**

This module is provided for use by the system administrator to allow the operation of the IMS system to be configured. On the host side, such a configuration would apply to the following modules:

- *anomaly detector*, e.g. behaviour characteristics to consider/prioritise, generic rules in operation;
- *profile refiner*, e.g. frequency of refinement, acceptable thresholds for challenges within a session; and
- *archiver*, e.g. level of detail required, specific events to record or exclude from logging.

For the client side, the operation of the following modules would be controlled:

- *collector*, e.g. the level of data collection (linked to the characteristics being monitored by the *anomaly detector*), and
- *responder*, e.g. the level of response required at each alert status level.

These settings would obviously be controlled and recorded through the host system. The configuration of the local client(s) would then be established at the time of session initiation.

In addition to the above, several other features would also be provided under the auspices of the *controller* module. These would include facilities such as user profile management, update of the generic rulebase and the like.

### **User profiles**

IMS profiles could conceivably hold a range of identification, authentication and behavioural information relating to legitimate users. The profiles would use a number of methods to represent measures of user behaviour:

- frequency tables (e.g. for file access);
- means and standard deviations (e.g. for keystroke/typing profiles);
- ranges (e.g. valid access times);
- lists (e.g. for valid access locations); and
- a combination of methods (e.g. a list of valid access locations which also indicate the relative frequency of use).

The profile data obviously require secure storage to prevent unauthorised browsing or tampering by potential impostors. If users were able to modify profile information it would be possible for them to adjust the records of other users to match their own (and, therefore, allow them to access the account in place of the legitimate owner). Whilst disclosure of the profile statistics may not initially appear to pose such a threat, it could still be a problem in the case of a determined impostor. For example, if the characteristics of the "target" user were known, the impostor would have a concrete statement of what he/she would be required to mimic. An alternative option would, of course, be to subsequently enlist the help of an accomplice with a comparable profile. At the very least, this dictates a requirement for encrypted storage, as used with the password files in the majority of commercial operating systems (Morris and Thompson, 1978).

**Issues related to intrusion monitoring**

This section presents further discussion of a number of the issues that were mentioned during the description of the IMS modules. The issues in question are the restriction of user activities, suspension of supervision and types of response to suspected intrusion.

**Restriction of user activities**

It is considered feasible for the alert status level to be inter-linked with the types of activity that a subject is allowed to perform, such that a phased reduction of permitted behaviour would occur as the level increases. In this way, highly sensitive activities and/or information could be denied if there is any doubt over the current user's legitimacy, whilst still allowing more mundane activities to continue. The approach would demand that a maximum alert status threshold be associated with each of the activities or objects that the IMS is to control. If the current status level was then to exceed this, the activity or object would become unavailable. For example, consider the thresholds in Table IV associated with two objects (wordprocessor and database) and the activities create and delete file. If the current alert status level were five then the user would not be permitted to access the database or to perform any file deletion. However, the creation of a file using the wordprocessor application would still be possible.

Such a threshold table would be maintained within IMS, but the values would initially need to be assigned (and, if necessary, subsequently updated) by the system administrator. It must be said that the potential for error would make this approach inappropriate in many scenarios (for example, the denial of data access in sensitive applications could be most unwelcome). In any case, it would be advisable for the system administrator to be notified whenever behaviour restrictions were being imposed so that the situation could be investigated (in case legitimate users were being unintentionally impeded).

**Table IV**  
Alert status threshold table

| Activity/object | Alert status threshold |
|-----------------|------------------------|
| Wordprocessor   | 8                      |
| Database        | 2                      |
| Create file     | 8                      |
| Delete file     | 3                      |

**Suspension of supervision**

In some cases it is envisaged that continuous behaviour monitoring at all times throughout a user session may not be strictly necessary or even advantageous. This is especially true in the case of the mechanisms aimed solely at the detection of penetrators (e.g. keystroke analysis). The rationale here is that, after a reasonable amount of uninterrupted behaviour analysis (i.e. with no challenges and no significant periods of user inactivity), the monitoring system should have been able to accurately determine the legitimacy of the current user (e.g. previous research has indicated that, using keystroke analysis, a reliable authentication judgement should be obtainable within 400 keystrokes in a real-time monitoring context (Furnell, 1995)). If an impostor is not suspected at this point then it is extremely unlikely that further monitoring will detect one (indeed, monitoring for longer than is necessary would simply allow more opportunity for false rejections to occur and place an additional load on the system). In view of this, it is considered that monitoring activity during the following periods is likely to be most crucial in terms of impostor detection (with supervision being temporarily suspended at other times):

- during the period immediately after the start of the session (when the authenticity of the user has yet to be conclusively proven);
- during the time after any significant period of inactivity (during which an impostor could potentially have replaced the legitimate user).

Important considerations here would obviously be the period of monitoring necessary before suspension of supervision and also what length of time would constitute the significant period of inactivity necessary for it to be resumed. Suggested periods would depend upon the monitored characteristics (e.g. monitoring of keystroke dynamics could yield an authentication judgement more quickly than monitoring of application usage), but a general rule could be to monitor up to five minutes of non-anomalous activity before suspension in order to allow a sufficient appraisal of the user to be made. Approximately two to three minutes of inactivity would then be seen as a suitable trigger for monitoring to resume, as this length of time could have allowed sufficient opportunity for impostor intervention. In a practical implementation, both of these aspects would be configurable so that the optimum levels could be established.

It should be noted that this approach would not be adequate for the detection of misfeasor activity, as this could very well proceed after authentication has been established.

Therefore, if suspension of monitoring was still to be incorporated, it would be sensible to periodically reintroduce supervision at random intervals as an additional safeguard (this would also help to guard against a situation where an impostor/penetrator might be able to replace the authorised user without there being a significant period of inactivity).

This idea is primarily suggested as a means of minimising the likelihood of false rejections in the practical context. However, a further advantage in the context of practical implementation would be that it would reduce the significant processing overhead that would be associated with continuous monitoring in an environment with a large number of client machines.

#### **Response to suspected intrusions**

The existence and operation of IMS should ideally remain transparent to the user unless an anomaly is suspected. As previously stated, a suspected intrusion will cause IMS to automatically perform some further action (the nature of which will vary depending upon the type of intrusion involved). Options here include:

- issuing of an explicit request (or challenge) for further authentication;
- recording of details in an intrusion log for later inspection/investigation;
- immediate notification of the system manager (i.e. an intrusion alarm);
- phased reduction of permitted behaviour;
- locking of the intruder's terminal;
- termination (or suspension) of the anomalous session/process.

The degree of automatic response is an important consideration and, as indicated above, must be matched to the severity of the suspected intrusion. For example, if there is high confidence that an activity represents an intrusion or if a particularly serious breach is suspected, then the maximum countermeasure response should result. However, in lesser scenarios more limited responses will be appropriate (e.g. simply writing details to the intrusion log).

There is an obvious danger that any option which allows the user to continue working whilst the anomaly is investigated would also allow more time for an intruder to cause damage. At the other extreme it would be undesirable for the system to terminate a session or process without a very high degree of certainty that an intrusion was in

progress. Therefore, the first two options above are considered to be the most appropriate as initial forms of response.

In practice, there are several possibilities for the type of challenge that the system could issue in the event of a suspected intrusion. The original system password would obviously be inadequate, given that it may have already been compromised in order for an intruder to have gained access in the first place. It is desirable that the challenge be such that it allows any legitimate user to resume work quickly with minimal interruption (i.e. it should be easy for them to overcome, whilst still trapping impostors). A suggestion is that a (short) series of question and answer type challenges be posed to the user (Haga and Zviran, 1991), who would then need to answer them correctly in order to proceed further. These could be based upon cognitive and/or associative information, with valid responses having been obtained and stored in conjunction with the original user profiling. If several (e.g. five to ten) such questions were to be obtained from users during profiling then the challenge could be based upon a random selection from the set (further reducing the chance of impostors being able to compromise the system).

There are, however, a number of scenarios in which this approach would be ineffective. Firstly, it must be remembered that any form of authentication-based challenge would be an inadequate countermeasure against misfeasors. They would obviously be able to respond correctly to such challenges (having originally supplied the information themselves) and then continue with unauthorised activity. There is a solution here in the realisation that continuing anomalies would lead to a succession of intrusion alerts; an event that would be suspicious in itself. At this point, the IMS response could then change to a method that would effectively combat misfeasors as well (e.g. a session lock or a trigger for system manager investigation). Nevertheless, this would still enable misfeasors to continue for longer than other classes of intruder (albeit with intermediate challenge(s)) before the system locks them out.

A second problem/exception relates to suspected malicious processes – these cannot be issued with a challenge to which they may respond and verify their legitimacy. This in turn places more importance on the correctness of the resulting IMS response (e.g. the dangers of suspending/deleting a legitimate, and possibly essential, process or failing to take positive action against a genuinely destructive one).

Finally, some classes of anomaly (for example, login failures based on unrecognised user identities) cannot be tied to a specific user and, as such, the issue of a challenge based upon profile information is again inappropriate. However, it is conceivable that some form of generic challenge could be issued (the answer to which would be known by legitimate system users), with invalid responses causing the IMS to proceed to its next level of countermeasure (e.g. system manager notification, terminal lockout).

### IMS implementation issues

The IMS concept is considered most appropriate to implementation in a networked environment, for the following reasons:

- Standalone systems will most often be dedicated to a single user. As such, more traditional authentication and access controls (e.g. passwords) will probably be sufficient to ensure security if they are correctly implemented.
- Implementation of a full IMS would be likely to degrade the performance of a standalone system.
- Networked systems provide more potential for collecting monitoring information. Many statistics (e.g. access location, resource usage) would not be appropriate to a standalone environment.

In this scenario, the host would be centralised with multiple IMS clients being used to monitor activity on the individual workstations. The purpose of the clients would be to collect any activity data that is generated locally (e.g. keystroke timings) and to enforce IMS restrictions in suspected intrusion scenarios (e.g. issue a challenge, lock access to the system etc.). In such a scenario it would be necessary to maintain the security of the IMS clients on the individual machines to ensure that their operation cannot be compromised (e.g. by a malicious user trying to avoid detection).

The realisation of the IMS approach is considered to have a number of advantages, as listed below.

- *Improved security.* This is advantageous in any information system, and is achieved here due to the continuous nature of supervision. User authentication is no longer restricted to the discrete judgement(s) possible with passwords' and misuse will be identifiable much earlier than with traditional auditing. In addition, the fact that much of the supervision is based upon behavioural

characteristics makes it more difficult for users themselves to undermine security (e.g. by allowing colleagues unauthorised access to their accounts) as they cannot easily transfer these abilities to other users.

- *Cost.* Advantages here result from the fact that it is possible to implement the concept entirely in software at the user end, whereas many frequently suggested authentication enhancement schemes (e.g. smart cards, other biometric methods) are reliant upon specialised equipment at each user workstation. This makes the technique particularly suited to financially constrained environments.
- *Convenience.* This comes from the fact that the supervision can be performed transparently, in a non-intrusive manner. In addition, the fact that the IMS would demand nothing special from the users (e.g. they are not required to remember additional password-type information or possess any physical token) means that its operation should not undermine the existing staff culture, which is recognised as an important issue in the introduction of security (Warren *et al.*, 1995).

There are also a number of inherent disadvantages in the concept of IMS (and, indeed, any other type of comprehensive monitoring and supervision system). The principal concerns are highlighted below.

- The operation of IMS clients and/or data collection will consume system resources and may degrade overall performance. The collection of detailed audit trail data typically degrades machine performance by between 5 and 20 per cent (Wolfe, 1992; Mukherjee *et al.* 1994). An IMS performing full behavioural monitoring and testing of generic intrusion rules would be envisaged to introduce a similar burden.
- Transmission of data from clients to the host will result in a loss of network bandwidth and a loss of timeliness of data.
- Maintenance of the IMS itself would entail a more significant management/administration burden in the affected systems. For example, correcting problems with behaviour profiles would be a more complex operation than cancelling a forgotten password. At the same time, however, other duties (such as inspection of audit trails) would be reduced, so the new demands would at least be somewhat offset.
- The overall concept of continuous supervision raises a question of user acceptance. It is conceivable that there may be mistrust and resentment of the

system on the grounds of it being seen as a means of monitoring legitimate work and staff performance as opposed to just guarding against intruders. It would, therefore, be important to ensure that the system is perceived as a caring mother rather than a big brother.

In general terms, the likely advantages when compared to other means of protection are considered sufficient to outweigh these points. In view of this, the authors are currently developing an implementation of the IMS approach for the Windows NT environment (Dowland and Furnell, 2000).

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## Conclusions

The paper has described the concept of intrusion monitoring and a potential approach by which it may be realised in modern networked systems. The IMS concept is not intended as a total replacement for conventional authentication and access control methods (although in some cases it will offer an opportunity for more dated approaches to be replaced). In the majority of systems, supervision could be incorporated alongside other methods to complement the security already provided. In addition, it will have little or no effect upon the need for physical security and personnel-related measures within an organisation. There are also some important aspects of logical security that are not addressed (e.g. protection of data communications) which further highlight the potential need for a wider IT security framework.

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## Note

See, for example, [http://www.securitysearch.net/Research\\_and\\_Education/Intrusion\\_Detection/](http://www.securitysearch.net/Research_and_Education/Intrusion_Detection/)

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