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A comparison of linear and logarithmic auditory tones in pulse oximeters

Zoe Brown[1], Judy Edworthy[2] & Robert Sneyd[3]

[1]Derriford Hospital, Crownhill, Plymouth, Devon PL6 8DH, UK

[2]School of Psychology, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, UK*

[3]Penninsula College of Medicine and Dentistry, Tamar Science park, Plymouth, Devon PL6 8BU, Devon, UK

*Corresponding author

Tel: 01752 584818

Email: jedworthy@plymouth.ac.uk

One of the key features of a pulse oximeter is that the audible tone emitted varies as the value of the blood oxygen saturation level varies, providing valuable auditory feedback for the clinician. However, many pulse oximeters use a linear mapping of frequency change (in Hz) to saturation change where the pitch of the tones appears to get closer the higher the saturation level becomes. In this study we compare the usual linear scales with a logarithmic one, where changes in saturation are indicated by pitch changes which are perceptually equivalent (each 2% change in saturation was indicated by a semitone change). The results show that anaesthetist participants produce more accurate mappings between tones and saturation levels and are more accurate at estimating the degree of saturation when a logarithmic, rather than a linear, scale is used.

1. Introduction

Pulse oxmietry is widely used in medicine. Pulse oximeters ~~typically~~ monitor arterial oxygen saturation, the percentage of arterial haemoglobin that is fully saturated with oxygen, ~~and pulse rate~~ by transmitting red and infrared light through the finger, ~~using this information to calculate the oxygen saturation of the blood~~. It is important in many medical procedures and has thus received considerable research attention. One application of pulse oximetry is for the monitoring of patients undergoing general anaesthesia. Pulse oximetry is an important tool to the anaesthetist as it aids rapid identification of decreased oxygen saturation within a patient, and may reduce critical events in patients undergoing general anaesthesia (Runciman, 1993; Cote, 1988; Morris, 1996). Acceptable oxygen levels vary between patients, depending on their physiology and any pathological processes, but any rapid falls in oxygen levels can have serious consequences, including death if not managed appropriately and quicly. In certain clinical situations, an oxygen level can be too high having equally damaging consequences. Thus the pulse oximeter is an invaluable tool for the anaesthetist to increase patient safety under general anaesthesia, particularly as It increases awareness of the anaesthetist and the operating team to the patient's physiological changes in a situation where there is often background noise and false alarms (Seagull et al, 2001). ~~For example, pulse oximetry has gradually become more sophisticated in terms of both the technology used to analyse the resultant waveforms (and hence the improvement in accuracy of readings and the reduction of false alarm rates) and in the expansion of physiological measurements that can be carried out via pulse oximetry (Cannesson & Talke, 2009).~~

The World Health Organisation has recognised the importance of the pulse oximeter, and now mandates the use of pulse oximetry during anaesthesia, and a project aimed at looking and encouraging pulse oximetry in middle- and low-income countries has led to increased uptake of pulse oximetry in those countries (Walker et al, 2009). This project, referred to as the 'Global Oximetry Project', which included users in Uganda, Vietnam, India and the Philippines, resulted in increased usage of pulse oximeters and also

provided data on the good and bad features of the oximeters used there. The project identified some key features which all pulse oximeters should possess: these were that an oximeter should have a long battery life, should have a pulse rate display, should be easy to clean and maintain, should be easy to use, should be durable, should work well when the patient is cold and when blood pressure is low, and have an audible pulse tone that changes with saturation (Walker et al, p. 1057). This paper is concerned with the last of those elements regarded as essential: the audible pulse tone that changes with saturation.

This use of a simple sonification (turning data into sound in a meaningful manner), where the pitch of the auditory tone changes with the level of oxygen saturation, was a relatively early design advance initially introduced by the Nellcor Corporation in 1983. The principle of this sonification is that, as oxygen saturation rises, so does the frequency of the tone use to indicate a change in saturation level. Subsequent research on variable pitch pulse oximeters indicated that most users were able to perceive this pitch change, and that the speed of response of the anaesthetist was reduced in comparison with a fixed-tone oximeter (Schulte & Block, 1992; Craven & McIndoe, 1999). These findings underpin the two main benefits of using variable-tone pulse oximetry. The first is that the variation in tone can tell the observer whether saturation is going up or down. A second, more subtle benefit is that the observer may be able to judge the degree of change in saturation by the degree of variation in the tone.

A review of some extensively-used pulse oximeters (Chandra et al, 2006) demonstrated that there is large variability in their acoustic properties. In all cases change in saturation levels was indicated by a change in tone, but the similarity ends there. Chandra et al found that some were louder than others, some produced a greater loudness range, and analysis of the spectrum revealed considerable variation in the harmonic content and complexity of the tones used. They also found variation both in the absolute pitch of the tones used and the way pitch varied as a result of changes in saturation. For example, the pitches of the tones indicating 85% saturation ranged from 375 to 844Hz, 90% from 422 to 938Hz and 99% from 469 to 1078Hz. Other studies have revealed similar variation (Santamore & Cleaver, 2004). Both Chandra et al and

Santamore & Cleaver suggest that this variation is likely to cause problems for anaesthetists when moving from one pulse oximeter to another.

Studies which have surveyed the audible tones used in pulse oximetry also highlight the fact that the degree and nature of the frequency change with change in saturation varies across oximeters. Santamore & Cleaver's study showed that the change in hertz per degree of saturation ranged from 4 to 21Hz, all of which are small and the lower of which are bordering on imperceptible. The difference between 95% and 100% saturation in some cases covers a pitch range of a single semitone, which is the smallest unit of difference on a piano (for example, between a white note and the nearest black note) . It is possible that such small pitch changes make it difficult for the anaesthetist to detect both the direction and presence of a change. Schulte & Block's finding (1992) suggest that the direction of change is typically detectable only about 2/3 of the time by anaesthetists using oximeters which use these small frequency changes.

Another important issue concerning the relationship between the audible tones used and the saturation levels which they represent is that, for the majority of pulse oximeters, the mapping between saturation change and frequency change is linear (Santamore & Cleaver, 2004). For example, some of the Datex oximeters showed a change of approximately ten hertz per degree of saturation, regardless of the saturation value being represented. The problem with using linear mappings between saturation change and frequency change is that pitch perception, which is the psychological correlate of the physical entity of frequency, is logarithmic rather than linear in nature. Differences in pitch which sound equivalent to the listener are based on fixed proportions rather than fixed numbers. For a difference in pitch between any two tones to be judged as equivalent, the increase in frequency must be the same proportion of the two frequencies. For example, for three octaves to be regarded as being successive octaves apart their frequencies (if the first one was 200Hz) would be 200Hz, 400Hz and 800Hz (doubling the frequency for each octave in the ratios 1:2:4) rather than 200, 400 and 600Hz (ratios of 1:2:3). For the semitone, which is the smallest unit of pitch difference typically used in music, the change in frequency from one tone to another a

semitone higher is approximately equivalent to {(first frequency)*twelfth root of two}. Thus, the higher the first tone, the greater the change in Hz required to produce a tone which is perceptually a semitone higher.

As the frequencies used in pulse oximetry tend to be based on a linear rather than a logarithmic mapping between saturation level and audible tone, this has the consequence that as saturation level rises, the perceptual difference between adjacent saturation levels becomes closer. There is evidence to suggest that anaesthetists' ability to judge saturation levels from the tones used in many commercially-available oximeters is compromised both by the very small frequency changes which are used and by the use of a linear rather than a logarithmic mapping. For example, Morris and Mohacsi (2005) played the tones used in a Datex AS3 pulse oximeter to anaesthetists and found that while anaesthetists were generally able to judge lower saturation levels as being lower than higher ones, the estimates of the actual saturation level represented by the tones was very compressed, so that the median perceived estimates for 70% saturation was 89%. Estimates for 80% saturation were 93%, but correct for 94%. Morris & Mohacsi also played anaesthetists pairs of tones and asked them to estimate the difference in saturation represented by those tones and found that the median estimate of difference between two tones representing a 20% change in saturation was 5%. They also found that as the difference between the two tones was reduced, the ability of anaesthetists to accurately record the direction of change (up or down) declined, with only 70% of direction judgements being correct for the smallest saturation difference presented, 2%. Morris and Mohacsi's data therefore suggests that a linear scale with small frequency differences leads to overestimation at the bottom end of the saturation scale, and underestimation of saturation change when two tones are presented in close temporal proximity, as well as lack of clarity of direction change with smaller saturation differences.

Morris and Mohacsi suggest that the use of a non-linear scale, such as a semitone scale, may prove more effective and should be tested. There are many reasons as to why a semitone scale might be more effective in representing saturation levels. The first is that the mapping between saturation levels and frequency change will be logarithmic, rather than linear, and thus the perceived pitch difference between two adjacent saturation levels (for example, a 2% change) will be perceptually constant. A second reason is

that if the semitone is used as the basic unit of change between adjacent saturation levels (again say 2%) then the difference between two close saturation levels will be represented by a much larger pitch change than is typically found in pulse oximeters, which should improve accuracy both in the detection of a direction change in saturation and the magnitude of the difference between two saturation levels. Thirdly, the semitone scale is used throughout western music and there is ample evidence to suggest that the extensive exposure to this scale, which is familiar to almost all listeners, leads to the establishment of mental templates, schemas and representations for pitch perception (Cross, 1997; Deutsch & Feroe, 1981; Krumhansl, 1990). In this paper we examine the relative efficacy of linear and logarithmic (semitone) scales as representations of pulse oximetry saturation levels.

2. Experiment One

Morris and Mohacsi presented anaesthetists who regularly used the oximeter from which the test tones were recorded (Datex AS3) with each of the tones representing 70% through to 98% saturation and found that they severely overestimated the saturation level associated with the lower-value tones. In our first study we use a similar linear set of tones but compare it with a set of semitones. In one condition saturation values from 70% to 100% are mapped to tones similar to those tested by Morris and Mohacsi. In the other, a set of adjacent semitones are mapped to the values from 70% to 100%. In both cases, the tones are mapped in 2% saturation intervals as the commercially-available instrument from which the linear tones were derived only changes tone with every 2% change in saturation.

Inevitably, using a semitone scale covers a wider range of pitch values than does the linear scale used so we took the decision to make the highest, rather than the lowest, pitch approximately the same for both scales. We also presented the entire range of tones to the participant before beginning the experiment, in order to enable them to more readily anchor their judgements. We also provided the middle tone, representing 86% saturation, before each of the tones was presented.

2.1 Method

2.1.1. Materials

Two sets of tones were designed, one a replica of those use by the Datex-Ohmeda AS/3 monitor (a linear scale) and one using a logarithmic semitone scale. The linear scale consisted of 16 tones representing saturation values between 70% and 100% in 2% increments. The tone assigned to 70% saturation was 620Hz, and each tone representing successively higher values was achieved by increasing the frequency in steps of 20Hz with every 2% increase in saturation. Thus 100% saturation was represented by a 920Hz tone.

The logarithmic scale also represented saturation values from 70% to 100%, with the relationship between successive levels represented by a change of a semitone (an increase in Hz from one step to the next equivalent to the 12th root of 2). The lowest saturation level, 70%, was represented by a tone of 390Hz and the highest, 100%, was represented by a value of 930Hz. Thus the value of the highest point was approximately equivalent for both scales, but the lowest point was lower for the logarithmic scale. Table 1 shows the frequency values representing each of the saturation levels tested. The waveform used for both scales was a square wave tone lasting 0.2 seconds followed by a 0.6 second pause, repeated three times. The total stimulus length was 2.6 seconds.

Insert Table 1 about here

2.1.2. Participants

Forty anaesthetists from a range of professional grades, with different levels of experience, participated in the study. Each participant underwent a pure-tone audiogram to check for any hearing problems (none were revealed). Tone presentation and data collection was automated using custom-written software on a personal computer. The tones were presented at a loudness level of approximately 75dB (A). Participants entered their responses using the computer keyboard. The experiment was conducted in a quiet room, with all participants undertaking experiment one, then experiment two directly after. Total experiment time for each participant was approximately 45 minutes.

2.1.3. Procedure

Once participants' hearing had been screened and they were seated at the computer with the headphones on, they were presented with one of the two sets of tones (either the linear or the logarithmic set, counterbalanced across participants). The tones were presented in both an ascending and descending order from 70% to 100% back to 70% (in 2% increments), which was then repeated. During this familiarisation, the saturation value represented by each the tones was shown on the computer screen. The experiment then began. In each trial, participants were presented with two tones. The first was always the tone representing 86% saturation (with participants being aware of this). The second tone was one of the values from 70% to 100% saturation. Participants were required to judge the saturation level represented by the second tone by typing in the value they thought that the tone represented. Each participant heard each of the tones representing 70% to 100% in a different random order, once. Once the participants had completed the task for the first scale used, they were given a short break. The whole procedure was then repeated, using the remaining scale. The included both familiarisation with the scale and the presentation of 16 trials, as before.

2.2. Results

Figure 1 shows the mean percentage saturation values estimated for the second tone across the two sets of tones for 40 participants, together with the (y = mx + c) line of best fit equation for each scale.

Insert Figure 1 about here

The equation for the linear scale regression line is y=0.7956x + 17.319 and the equation for the logarithmic regression line is y=0.9777x + 1.4688. Thus the logarithmic line is much closer to y=x, the line of identity, meaning that the estimates of saturation were more accurate for the logarithmic scale than for the

linear scale. The larger constant value associated with the linear scale (> 17) suggests that saturation values are overestimated at lower saturation levels for the linear scale.

A two-way scale (linear vs logarithmic) x percentage value (70% to 100%) within-subjects ANOVA on the percentage error scores (the difference between the actual value of the tone and the estimate given) showed that there was a main effect for scale ($F = 23.95$, df = 1, $p < 0.001$) with mean errors being 2.4% for the linear and 1.63% for the logarithmic scale. There was also a main effect for percentage ($F = 16.82$, df = 15, $p < 0.001$) whereby participants' errors across the two scales tended to be smaller in the mid-region than at the extremes of saturation value. There was also an interaction between scale and percentage value ($F = 3.98$, df = 1, 15, $p < 0.001$) whereby the percentage error at the extremes of the scales was higher for the linear than the logarithmic scale (Figure 2).

Insert Figure 2 about here

2.3. Discussion

The main effect for scale indicated that the accuracy of estimates was higher for the logarithmic, semitone scale than for the linear scale. Mean errors in estimation were 2.4% for the linear scale and 1.63% for the logarithmic scale. The main effect for percentage indicated that, for both scales, estimates were more accurate in the middle of the scale. We might expect this on the basis that the tone representing the middle saturation level, 86%, was presented before the tone to be guessed in each trial. However, the interaction between scale and percentage shows that accuracy at the extreme values was less good in general for the linear scale than for the logarithmic scale (Figure 2). Interestingly, for both scales, but particularly for the logarithmic scale, performance was more accurate at the 70% level, suggesting that participants had some awareness of the pitch values at the end of the scale and were using them as anchors, making it easier to make these judgements.

The line of best fit equations indicate that estimates were also more compressed for the linear than for the logarithmic scale. The line of best fit for the linear scale was y=0.7956x + 17.319, suggesting that participants overestimated at the lower end and underestimated at the higher end. The line of best fit for

the logarithmic scale was y=0.9777x + 1.4688, which is most closer to x = y, indicating that estimates more closely mirrored the actual saturation values presented, a finding also borne out by the ANOVA.

Our results are similar to those of Morris & Mohacsi (2005) in that they demonstrate that saturation estimates are both inaccurate and compressed for linear scales. The linear tones tested in this study were from the same instrument as that tested by Morris and Mohacsi. Errors are however much smaller in our study. This is likely to be because we presented the range of pitches used before the experiment proper began, allowing the listener to form a frame of reference and to establish anchors. Judgements at the extreme ends of saturation suggest that these anchors were useful for the listener, as their judgements were somewhat more accurate for the top and bottom saturation values in comparison with those values immediately surrounding them. Secondly, we presented listeners with an anchoring tone (the 86% saturation tone) prior to the tone-to-be-judged, which would also have helped improve the accuracy of responses.

3. Experiment 2

In the second experiment, we investigated the effect that the two different scales might have on anaesthetists' ability to estimate the difference between two tones presented one after another, simulating a situation where saturation values change. Morris and Mohacsi (2005) performed a similar study using only a linear scale, and demonstrated that participants typically considerably underestimated the degree of saturation change. Anaesthetists became more accurate in detecting the direction of change as the percentage change increased, but significantly underestimated the amount of saturation change for both small and large saturation changes. The median estimate for a 20% change in saturation was 5%.

In our second experiment we presented the same listeners with thirty pairs of tones where the saturation change was 2, 6 or 10% downwards or upwards. The first tone was always within the range of 86% to 100% as these values represent higher-than-critical values, with changes downwards representing potentially clinically-relevant changes (Welch, 2011). This also made it easier to counterbalance upward and

downward pitch direction across the starting saturation levels tested. Listeners were again presented with the scales (86% to 100%) for familiarisation.

Participants initially heard each tone (from 86% - 100%) for both the linear and the logarithmic scales and were asked to estimate its percentage saturation value. They were then presented with a second, different tone representing a deviation of 2, 6 or 10% (unbeknown to the participants) either upwards or downwards, and were asked to estimate the second value in percentage saturation.

3.1. Method

3.1.1. Participants

40 anesthetists participants took part in this study. They had all previously participated in Experiment 1.

3.1.2. Materials

Two scales, one logarithmic and one linear, were used as in Experiment 1 (Table 1).

3.1.3. Procedure

Participants were presented with either the linear or the logarithmic tones first, with half hearing the linear tones first and half hearing the logarithmic tones first, as in Experiment 1. Prior to the start of the experiment each participant was played each of the tones from 86% to 100% twice, once ascending and once descending, with the appropriate saturation level appearing on the screen as the tone was played. The experiment proper then began. In each trial, participants heard a tone from the 86% to 100% saturation level range and were asked to estimate the percentage saturation represented by that tone. After a short pause, they were presented with a second tone which could be any of the saturation levels from 70% to 100% other than the tone they had just heard (so there were no trials in which the first and second saturation levels were the same). They were asked to estimate the direction (drop or rise) and the percentage change in saturation represented by the difference between the first and second tone, which they entered into the computer. Participants heard thirty pairs of saturation tones for the scale in total. Fourteen of the changes were 2% changes in saturation, seven up and seven down; ten were 6% changes in saturation (five up and five down); and six of the changes were of 10% (three up and three down).

Once the 30 trials had been completed, the procedure was completed in full for the other scale.

3.2. Results

The accuracy of the responses to the first of the two tones in the pair is useful for replication and comparison purposes with Experiment 1. Second, the results consider the ability of participants to indicate the direction of change. Thirdly, we consider their accuracy in estimating the degree of saturation change between the first and the second tone.

3.2.1. *Estimation of first tone*

Figure 3 shows the mean saturation estimate for each tone in each of the two scales.
The equation for the linear scale regression line is $y=0.5954x + 37.252$ and the equation for the logarithmic scale regression line is $y=0.7708x + 20.924$. Again the logarithmic scale is closer to $y=x$, the line of identity. For both scales the lower values were overestimated and the higher values underestimated, but this was more pronounced for the linear than for the logarithmic scale. Performance is overall not as accurate as in Experiment 1.

A two-way scale x percentage within-subjects ANOVA on the mean error percentage estimates (as in Experiment 1) showed a main effect for scale ($F = 55.55$, df = 1, $p < 0.001$). The mean estimation errors were higher for the linear scale (2.46%) compared with the logarithmic scale (1.75%). Again these results are similar to those obtained for Experiment 1, where mean errors were also higher for the linear than for the logarithmic scale.

Insert Figure 3 about here

There was no effect for percentage. A significant interaction was obtained between tone and percentage ($F = 2.7$, df = 1, 7, $p < 0.05$). As for Experiment 1, performance was less accurate at the extreme values for the linear scale but was relatively consistent for the logarithmic scale (Figure 4), even though in this study we used only the upper half of the scale.

Insert Figure 4 about here

3.2.2. *Judging the direction of change in saturation*

Table 2 shows the percentage accuracy in judging the direction of saturation change from first to second tone for each of the scales (higher or lower). Performance was very high for each of the scales, but higher for the logarithmic than for the linear scale.

Insert Table 2 about here

3.2.3. *Estimation of saturation change*

Table 3 shows the mean error in estimates of saturation change as a function of the value of the first tone. A two-way scale x percentage (first value) ANOVA gave a significant effect for scale ($F = 61.27$, df = 1, $p < 0.001$). Performance was more accurate using the logarithmic scale than the linear scale, with mean errors of 1.47% and 2.1% respectively. A significant effect for percentage was obtained ($F = 16.27$, df = 7, $p < 0.001$) whereby performance was worst at the ends of the scales and more accurate in the middle. There was no interaction between scale and percentage.

Insert table 3 about here

4. Discussion

Experiments 1 and 2 demonstrate that the use of a logarithmic, semitone scale produces lower mean error estimates both of absolute values of saturation and percentage change estimate errors when compared with a linear (and smaller) scale. In terms of absolute estimates of saturation value, performance was better (errors in estimation were lower) when using the logarithmic, rather than the linear, scale. In terms of the mapping of actual value to estimated value, the logarithmic scale performed better than the linear scale. Our results also show that anaesthetists' estimates of percentage change in saturation level are

more accurate when using a logarithmic scale than using a linear scale. Thus our results confirm the intuition that a perceptually-spaced logarithmic frequency scale would lead to better performance.

Our participants performed considerably more accurately on the linear scale than those who participated in Morris and Mohacsi's study (2005) but there are notable methodological differences between the two studies. These differences have practical application. In Morris and Mohacsi's study, participants were not given the range of values to listen to prior to the start of the experiment; thus they were unable to use any anchors for making their judgements and thus had to rely on their memory for the particular set of pitch values associated with the oximeter tested. The combined effect of people's poor memory for absolute pitch (Deutsch, 1972) combined with a typical exposure to more than one oximeter on a day-to-day basis would have significantly increased participants' inaccuracy relative to ours. The implication of this is that presenting practitioners with the range of tones used prior to use may represent good practice by allowing practitioners to anchor their judgements once the oximeter is used, thus reducing the size of their errors. This practice would take only a few seconds. The second difference between ours and Morris and Mohacsi's study is that, at least in the first study, we presented participants with the central saturation tone, 86%, prior to each trial. This too will have helped listeners to anchor their judgements.

Although we are largely attributing the better performance on the logarithmic scale to the use of a semitone scale which is both overlearned in Western culture and, critically, possesses perceptually equivalent pitch changes between the saturation levels, the pitch differences between the 2% values were also greater for the logarithmic than for the linear scale. Our data however (Table 2) shows that the most simple of the judgements required, that of whether the pitch change was upwards or downwards in direction, was performed well for both scales (and better than participants in Morris & Mohacsi's study). This in turn suggests that the very small pitch differences associated with the linear scale are at least functional in giving directional information, though not as good as the logarithmic scale. The better performance of our participants may have been due to the better anchoring provided, and their previous and recent exposure to the scales (all participants in Experiment 2 had previously participated in Experiment 1). This suggests that it is not just the smaller size of the pitch steps *per se* that make performance on the

linear scale worse than the logarithmic scale on all of the judgements that we measured, as participants are still able to perceive those changes. An experiment where the range of pitches covered is the same for both scales (but with one still linear and the other logarithmic) is possible, and may clarify the issue as to the relative contributions of step size and type of scale, but makes little practical sense when we already have an overlearned and familiar semitone scale at our disposal.

Our results show that using a pitch scale based on the musical semitone improves the accuracy of both absolute judgement of saturation value and relative judgement of saturation change. The practical implication of this is that pulse oximeters, which continue to

use linear scales, are not taking advantage of known and useful features of auditory cognition. To increase

patient safety, it is firstly important that pulse oximetry tones are standardised.

Not all pulse oximeters use a linear scale, or even

the same linear scale.

Anaesthetists rely on hearing changes in the pulse oximeter tone to focus their attention to the monitor and

hearing changes in the pulse oximeter tone to focus their attention to the monitor and thereby to changes in

their patient's physiological state. In some clinical situations, the anaesthetist can be undertaking more than

one task at once and not concentrating solely on the patient's physiology. In other situations, the

anaesthetist may be unable to see the patient and so depend entirely on the monitoring, in particular the

pulse oximeter for information on how the patient is. As mentioned in the introduction, any changes in a

patient's oxygen level need to be managed quickly and effectively to prevent harm. A

logarithmic scale appears to outperform a linear scale on every judgement that clinicians might need to

whether the use of critical-point alarms, continuous sonification, or something between the two (such as the typical simple variable-pitch sonification found in many pulse oximeters) is the most appropriate approach. In conditions where such technology is not available (such as indicated in the Global Oximetry Project), a simple variable-tone pulse is likely to be of benefit and, where it is used, a logarithmic scale appears to outperform a linear scale on every judgement that clinicians might need to make and so it could be argued, that if standardisation of pulse oximetry was to occur, then the introduction of a logarithmic scale would further improve the reliability of this vital piece of equipment for patient safety.

5. References

Cannesson, M., Talke, P., 2009. Recent advances in pulse oximetry. F1000 Medicine reports, 1: 66

Chandra, D., Tessler, M., Usher, J., 2006. Audio spectrum and sound pressure levels vary between pulse oximeters. Canadian Journal of Anesthesia, 53(10, 26-32.

Cote, C.J., Goldstein, E.A., Cote, M.A., Hoaglin, D.C., Ryan, R.F., 1988. A single-blind study of pulse oximetry in children. Anesthesiology, 68(2), 184-8.

Craven, R., McIndoe, A., 1999. Continuous auditory monitoring – how much information do we register? British Journal of Anaesthesia, 83, 747-9.

Cross, I., 1997. Pitch schemata. In Perception and Cognition of Music Ed. I Deliege & J. Sloboda. Hove: Psychology Press.

Deutsch, D., 1972. Effect of repetition of standard and of comparison tones on recognition memory. Journal of Experimental Psychology, 93(1), 156-162

Deutsch, D., Feroe, J., 1981. The internal representation of pitch sequences in tonal music. Psychological Review, 88, 503-22.

Krumhansl, C., 1990. The Cognitive Foundations of Musical Pitch. Oxford: Oxford University Press

Morris, R., Mohacsi, P., 2005. How well can anaesthetists discriminate pulse oximeter tones? Anaesthesia and Intensive Care, 33(4), 497-500.

Morris, R.W., Montano, S.R., 1996. Response times to visual and auditory alarms during anaesthesia. Anaesthesia and Intensive Care, 24(6), 682-4.

Runciman, W.B., Webb, R.K., Barker, L., Currie, M., 1993. The pulse oximeter: Applications and limitations, an analysis of 2000 incident reports. Anaesthesia and Intensive Care. 21(5), 543-50.

Santamore, D., Cleaver, T., 2004. The sounds of saturation. Journal of Clinical Monitoring and Computing, 18, 89-92.

Schulte, G., Block, F., 1992. Can people hear the pitch change on a variable pitch pulse oximeter? Journal of Clinical Monitoring and Computing, 8, 198-200.

Seagull, F.J., Sanderson, P.M., 2001. Anesthesia alarms in context: An observational study. Human Factors: The Journal of the Human Factors and Ergonomics Society, 43, 66-78.

Walker, I., Merry, A., Wilson, I, et al., 2009. Global oximetry: an international anaesthesia quality Improvement project. Anaesthesia, 64, 1051-60.

Watson, M., Sanderson, P., 2007. Designing for attention with sound: Challenges and extensions to ecological interface design. Human Factors, 49(2), 331-346.

Welch, J., 2011. An evidence-based approach to reduce nuisance alarms and alarm fatigue. Horizons, Spring 2011, 46-52.

Oxygen Saturation	Linear scale frequency (Hz)	Logarithmic scale frequency (Hz)
70%	620	390
72%	640	415
74%	660	440
76%	680	465
78%	700	490
80%	720	520
82%	740	550
84%	760	585
86%	780	620
88%	800	655
90%	820	695
92%	840	735
94%	860	780
96%	880	825
98%	900	875
100%	920	930

Table 1: Frequencies (Hz) for the linear and logarithmic scale, representing each oxygen saturation level.

Linear Scale		Logarithmic Scale	
Direction	% Correct Identification	Direction	% Correct Identification
Higher	96.17	Higher	99.33
Lower	98.67	Lower	99.67

Table 2 : Percentage correctly identified direction changes for linear and logarithmic scales for Experiment 2

First Tone	Linear Scale % Error in Change in Magnitude Estimation	Logarithmic Scale % Error in Change in Magnitude Estimation
86%	2.58	2.00
88%	1.96	1.09
90%	2.10	1.30
92%	1.39	1.00
94%	1.29	0.99
96%	1.91	1.36
98%	1.75	1.44
100%	2.58	1.78

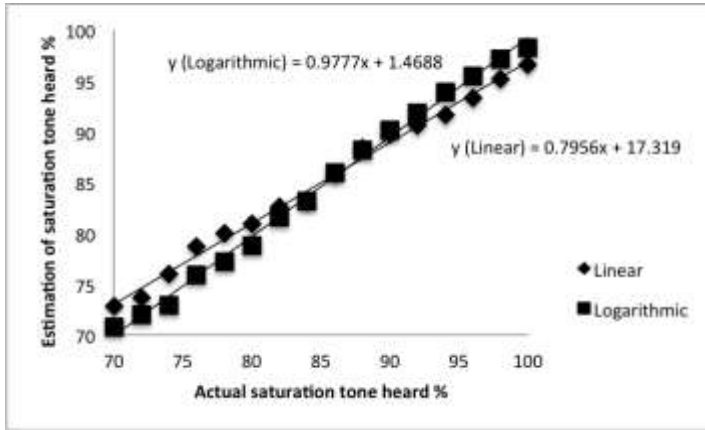Table 3: Error in estimation of change in magnitude from first tone to second tone for each scale in Experiment 2.
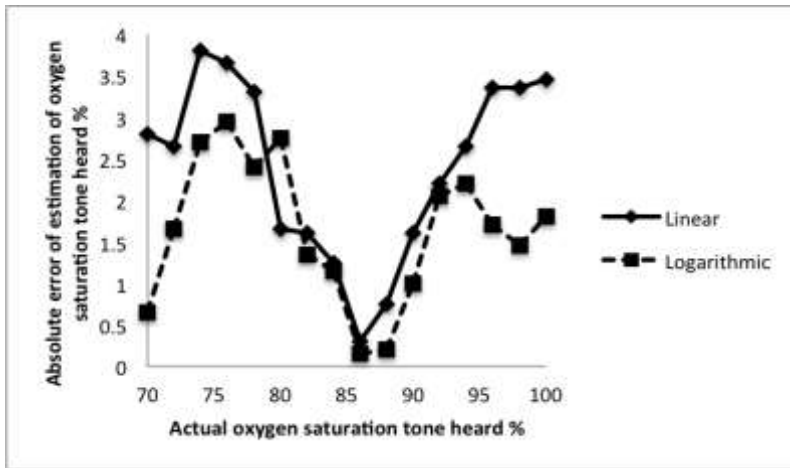
Figure 1: Actual oxygen saturation level heard versus estimated saturation level for each tone scale, with regression lines (Experiment 1)

Figure 2: Absolute error in estimated oxygen saturation using logarithmic and linear tone scales (Experiment 1)
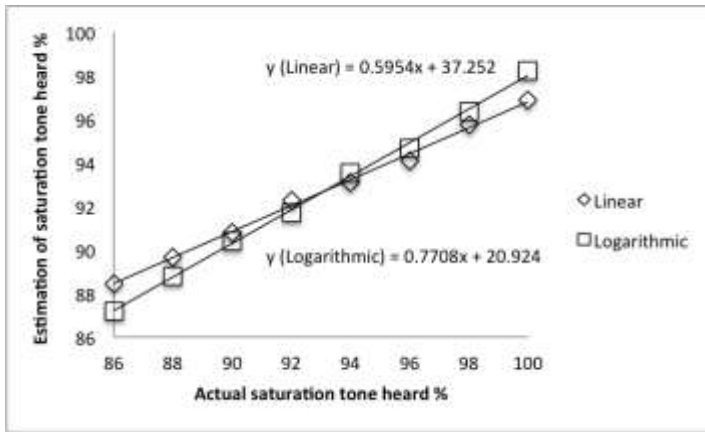
Figure 3: Actual versus estimated oxygen saturation for each tone scale, with regression lines (Experiment 2)
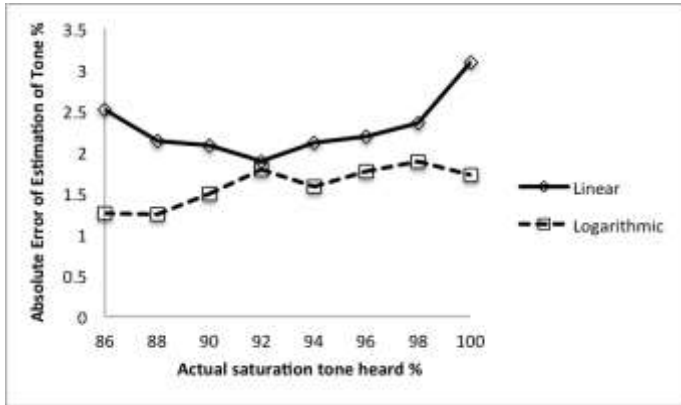
Figure 4: Absolute error in estimated oxygen saturation level of the first tone using logarithmic and linear

tone scales (Experiment 2)

A comparison of linear and logarithmic auditory tones in pulse oximeters

Zoe Brown, Judy Edworthy & Robert Sneyd

Highlights

- Pulse oximeters are used throughout medicine
- Though one of the earliest devices to incorporate auditory feedback, many commercial instruments use linear mapping of tones to saturation levels, This has the perceptual effect of tones appearing closer together, the higher the saturation rate rises
- We tested anaesthetists' ability to judge absolute values of saturation, and percentage change in saturation, using both linear mapping and logarithmic mapping, where the relationship between saturation change and pitch change is constant
- The results indicated that logarithmic mappings led to both more accurate estimations of saturation, and more accurate estimations of saturation rate change
- Use of logarithmic tone scales, for example a semitone scale, could be used more extensively in practice