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## An observational study of implicit motor imagery using laterality recognition of the hand after stroke

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13 **Title:** An observational study of implicit motor imagery using laterality recognition of  
14 the hand after stroke

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**Abstract**

**Objective:** To explore the relationship between laterality recognition after stroke and impairments in attention, 3D object rotation and functional ability.

**Design:** Observational cross-sectional study

**Setting:** Acute care teaching hospital

**Participants:** Thirty-two acute and sub-acute people with stroke and 36 healthy, age-matched controls.

**Interventions:** Not applicable

**Main Outcome Measures:** Laterality recognition, attention and mental rotation of objects. Within the stroke group, the relationship between laterality recognition and functional ability, neglect, hemianopia and dyspraxia were further explored.

**Results:** People with stroke were significantly less accurate (69% vs 80%) and showed delayed reaction times (3.0secs vs 1.9secs) when determining the laterality of a pictured hand. Deficits either in accuracy or reaction times were seen in 53% of people with stroke. The accuracy of laterality recognition was associated with reduced functional ability ( $R^2=0.21$ ), less accurate mental rotation of objects ( $R^2=0.20$ ) and dyspraxia ( $p=0.03$ ).

**Conclusion:** Implicit motor imagery is affected in a significant number of patients after stroke with these deficits related to lesions to the motor networks as well as other deficits seen after stroke. This research provides new insights into how laterality recognition is related to a number of other deficits after stroke, including the mental rotation of 3D objects, attention and dyspraxia. Further research is required to determine if treatment programs can improve deficits in laterality recognition and impact functional outcomes after stroke.

**Key Words:** stroke, perception, attention

1 **Abbreviations:**

2 Connor's Continuous Performance Test II (CCPT)

3 Hand Laterality Recognition Task (HLRT),

4 Catherine Bergego Scale (CBS).

5 Modified Barthel Index (MBI)

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1 Stroke is a leading cause of disability worldwide [1] , with over one third of survivors  
2 continuing to be functionally dependent a year after the stroke [2]. Only 12% of  
3 people with stroke with an initial upper limb motor deficit achieve complete functional  
4 recovery, while 38% regain some dexterity in the affected upper limb  
5 [3]. Understanding factors affecting functional deficits will aid in the targeting of  
6 future interventions.

7 Motor imagery can be divided into explicit motor imagery or implicit motor  
8 imagery[4]. Explicit motor imagery, or mental practice has been shown to be an  
9 effective treatment for the upper limb when combined with conventional therapy after  
10 stroke [5] [6-8]. Implicit motor imagery is most commonly assessed by the Hand  
11 Laterality Recognition Task (HLRT), which involves identifying whether pictures of a  
12 body part are left or right [4, 9-11]

13 Deficits in laterality recognition have been shown after a stroke [4, 12-20]. After a  
14 stroke, participants are less accurate [4] and slower in the hand laterality recognition  
15 task [13] however, even with severe hemiparesis, participants are able to use implicit  
16 motor imagery to solve a task [19]. Motor imagery recruits the same neural  
17 networks as those involved in movement execution [21] including the supplementary  
18 motor area, prefrontal cortex, premotor cortex, parietal cortex, cingulate cortex,  
19 cerebellum and inferior frontal cortex [8, 21]. Given the common neural networks  
20 involved in laterality recognition and motor planning/production, deficits in laterality  
21 recognition may be associated with deficits in functional movements although this  
22 relationship has not been explored to date.

23

24 Laterality recognition relies on the mental rotation of hands to solve the task and has  
25 been compared to the ability to mentally rotate objects using visual imagery after  
26 stroke. Using fMRI Kosslyn et al (1998) showed separate neural processes in these  
27 2 tasks; the rotation of hands recruited motor processing areas, whereas the rotation  
28 of objects recruited visual processing areas [22]. A double dissociation between the  
29 ability to perform motor and visual imagery has been shown in some studies with  
30 people with stroke specifically selected according to the area of damage [14, 16, 17].  
31 However, De Vries et al (2011) showed that people with stroke may have  
32 impairments in motor imagery, visual imagery or both at 3 or 6 weeks post stroke [4].

1 As reported in other patient groups (eg amputees [23]) it may be that people with  
2 stroke use a visual transformation of the stimuli rather than motor imagery to solve  
3 the laterality recognition task.

4 Impaired laterality recognition could also be associated with other deficits that are  
5 present after stroke, such as neglect or attention. Vromen et al (2011) found that in  
6 20 participants with right hemispheric lesions, patients with neglect did not perform  
7 as well in a hand laterality recognition task as patients without neglect [12]. They  
8 also found that the group with neglect scored significantly less on the tests of  
9 attention, however it was not mentioned if the attention impairment correlated with  
10 the impairment in motor imagery ability.

11 In summary, the relationship between a stroke and laterality recognition remains  
12 unclear. There is limited evidence about how laterality recognition after a stroke is  
13 related to visual imagery and the presence of other deficits such as neglect or  
14 sustained attention. Finally, the relationship between laterality deficits and function  
15 has not been explored to date.

16

17 Laterality deficits are seen in other conditions such as chronic regional pain  
18 syndromes where the deficits are felt to reflect brain re-organisation over time. In  
19 such conditions training of laterality recognition in combination with other techniques  
20 such as motor imagery lead to reductions in the primary impairment (pain) and  
21 improvements in hand function[24]. If laterality recognition is related to impaired  
22 function following a stroke it could be that similar interventions could be trialled in the  
23 future with the aim of improving motor control and functional ability.

24

25 The aims of the study are to (a) investigate the relationship between laterality  
26 recognition and potential causative factors such as impaired ability to mentally rotate  
27 objects or to sustain attention on a task; and (b) investigate the relationship between  
28 laterality deficits and functional ability.

## 29 **Methods**

30 A prospective observational cross-section design compared laterality recognition  
31 ability in people with a stroke and a healthy age-matched control group.

1 Inclusion criteria included radiological evidence of a stroke within the last 12 months  
2 and the ability to provide informed consent to participate in the study. Major  
3 exclusion criteria included previous stroke, pre-existing cognitive impairments, or  
4 patients who were medically unstable. Prospective sampling occurred with  
5 consecutive people with a stroke admitted to the stroke or the rehabilitation unit at a  
6 metropolitan hospital assessed.

7

8 The study was approved by the relevant Health Service Human Research Ethics  
9 Committee as well as Plymouth University, Faculty of Health, Education and Society  
10 Health Student Ethics Sub-Committee. All participants were provided with an  
11 information sheet and signed a consent form to participate in the study.

### 12 **Hand Laterality Recognition**

13 Implicit motor imagery ability was assessed using a hand laterality task (Recognise  
14 program, Neuro Orthopaedic Institute, 2011). Colour photographs of a hand in  
15 different positions were displayed on the screen and the subject responded by  
16 pressing the 'a' key for a left hand image or the 'd' key for a right hand image on a  
17 keyboard. The images were displayed on the screen until the subject responded up  
18 to a maximum of 10 seconds. Participants completed 4 blocks of 30 images  
19 randomly selected from the bank of 197 images in the program. The accuracy  
20 (percentage of correct responses) and reaction times were analysed. Reaction  
21 times below 150ms were excluded from the data (3% of responses).

### 22 **Mental Rotation of 3D objects**

23 Two pictures of Shepard-Metzler objects [25] that were rotations and/or reflections of  
24 a 10-block base object were displayed using Psychopy2. The participants  
25 responded with the 'a' key if the two objects were the same and the 'd' key if the  
26 objects were different. Each pair of 3D objects was shown for a maximum of 7  
27 seconds. Eighty unique pairs of images were shown from a bank of 15 rotations of  
28 the base object.

### 29 **Sustained Attention**

30 Sustained attention was assessed using the computerised Connor's Continuous  
31 Performance Test II (CCPT) (Version 5, Multi-Health Systems Inc). Participants  
32 responded by pressing the space bar on a keyboard when letters, except for the

1 letter 'X', were displayed on the screen. A practice session was completed for 70  
2 seconds prior to the 14 minute assessment period. Reaction time and a composite  
3 attention score ("Confidence Index") was calculated to determine the percentage  
4 likelihood that the subject fits a clinical picture of attention deficits or a non-clinical  
5 picture.

## 6 **Clinical assessment of deficits**

### 7 **Neglect**

8 The presence of neglect was assessed using the Catherine Bergego Scale  
9 (CBS). This scale has been found to be valid and reliable in sub-acute and chronic  
10 people with a stroke, and correlates to, but is more sensitive than conventional pen  
11 and paper tests of neglect [26]

### 12 **Function**

13 Function was measured using the Modified Barthel Index (MBI) which is an adapted  
14 version of the Barthel Index with improved sensitivity and reliability [27].

### 15 **Lesion location and other deficits**

16 The side of the lesion and lesion location was determined from MRI scans and  
17 reports. Documentation of hemianopia, dysphasia and dyspraxia was sourced from  
18 the medical record.

### 19 **Procedure**

20 The computer based assessments commenced with the CCPT, the laterality  
21 recognition assessment, and then the 3D object rotation. During the assessments  
22 participants sat supported in a chair with the arm that was not involved in the  
23 assessment positioned supported with the palm down. To reduce the impact of  
24 dysphasia, written cue cards were provided underneath the monitor with the letter  
25 and response key for the assessments for laterality recognition and 3D  
26 rotation. People with a stroke responded with their unaffected hand, which was  
27 defined as the hand ipsilateral to a cerebral/hemisphere stroke or contralateral to a  
28 medullary or cerebellar stroke, even if they did not have any residual weakness/inco-  
29 ordination. Images were presented in the spared visual hemifield for people with  
30 hemianopia. Control participants responded with the hand indicated by the  
31 researcher; a similar proportion of dominant/non-dominant response hands to the



1 stroke group were selected. Clinical assessments were completed within 2 days  
2 following the computer based assessment.

3

#### 4 **Sample Size**

5 Sample size was based on Reinersmann et al. (2009) who assessed laterality  
6 recognition in Chronic Regional pain syndrome. Reactions times in the chronic pain  
7 group ( $2.3s \pm 0.8$ ) were significantly longer than the healthy controls ( $1.8s \pm 0.5s$ ).  
8 Assuming a similar effect size (0.73) when comparing the stroke group with controls,  
9 a sample size of 30 in each group (stroke and healthy controls) was required  
10 (power=0.8, $\alpha$ =0.05)

11

#### 12 **Data Analysis**

13 Statistics were analysed using SPSS 18.0. Group differences were examined  
14 unpaired t-tests (e.g. age, 3D rotation, attention reaction time) or chi-squared  
15 tests(e.g. gender and hand dominance )

16 Three separate between group (stroke vs. control) repeated measures analysis of  
17 variances (ANOVA) for laterality recognition accuracy and reaction time were  
18 performed. The laterality of the pictured hand were separately analysed using the  
19 factors left vs. right hand; dominant vs. non-dominant hand; affected vs. unaffected  
20 hand. To analyse the data for pictures of the affected vs. unaffected, the unaffected  
21 hand was considered to be the response hand, with control participants analysed in  
22 the same way.

23 Participants with deficits in laterality recognition accuracy or reaction time, 3D object  
24 rotation and reaction time for attention were defined by scores that were 2 standard  
25 deviations below the mean for the control group. Participants were defined as  
26 having a deficit if they scored greater than 0 on the CBS for neglect.

27 Correlations were calculated between laterality recognition accuracy and reaction  
28 times with attention reaction time and 3D rotation accuracy with Pearson's  
29 correlation co-efficient. As the data was not normally distributed, a Spearman's  
30 correlation coefficient explored the relationship with function. Data is summarised as  
31 the mean  $\pm$  standard deviation; significance is taken as  $p \leq 0.05$

1

## 2 **Results**

### 3 **Participants**

4 Over a 6 month period 121 patients were admitted of these 34 patients fit the  
5 inclusion criteria. One patient was discharged prior to being invited to participate in  
6 the research, 33 consented to the research, but 1 patient withdrew after completing  
7 the practice for the attention assessment. Thirty-two people with a stroke (mean age  
8 =  $64.9 \pm 13$ ) and 36 control participants (mean age =  $61.1 \pm 15$ ) were therefore  
9 assessed. Group characteristics are summarised in Table 1.

10 There was no significant difference between the stroke and control group for age  
11 ( $t(66)=1.10$   $p=0.28$ ). There was a significant difference between the stroke and  
12 control group for gender ( $p=0.006$ ) with more males in the control group and more  
13 females in the stroke group. There was no significant difference for dominant hand  
14 ( $p=0.78$ ), with the majority of participants reporting right hand dominance. In the  
15 stroke group the average time since stroke was  $18.2 \pm 29$  days with a range of 2 to  
16 135 days and a median of 7 days. 81% of people with a stroke were assessed less  
17 than 3 weeks post stroke. The characteristics of people with a stroke are shown in  
18 Table 2.

### 19 **Group Analysis**

#### 20 **Laterality recognition accuracy**

21 There was a significant effect of group ( $F(1,66)=14.7$ ,  $p<0.001$ ) with the mean  
22 accuracy scores lower for the stroke group ( $68.6\% \pm 15\%$ ) than the control group  
23 ( $80.1\% \pm 12\%$ , table 3). There was no significant difference between recognising the  
24 laterality of a picture of the left or right hand, dominant or non-dominant hand, or  
25 affected or unaffected hand and there were no significant interaction effects. Ten  
26 (31.3%) participants in the stroke group were below the cut off value for laterality  
27 recognition accuracy of 57.4%.

#### 28 **Laterality recognition reaction times**

29 Reaction times for laterality recognition were slower in the stroke group ( $2.96$   
30 seconds  $\pm 1.4$ secs) than the control group ( $1.86$ secs  $\pm 1.05$ secs,  $F(1,66)=14.1$ ,  
31  $p=0.001$ , table 3). There was a significant effect of hand when recognising pictures

1 of left vs. right hand ( $F(1,66)=8.10, p=0.006$ ) and dominant vs. non-dominant hand  
2 ( $F(1,66)=6.0, p=0.02$ ). Faster reactions times were seen with the right and dominant  
3 hand. There was no difference between affected vs. unaffected hand ( $F(1,66)=0.56,$   
4  $p=0.81$ ). There were no significant interactions for hand\*group for each of the above  
5 analyses (left vs. right: ( $F(1,66)=0.01, p=0.93$ ); dominant vs. non-dominant:  
6 ( $F(1,66)=0.24, p=0.62$ ) and affected vs. unaffected: ( $F(1,66)=2.61, p=0.11$ ). Eleven  
7 participants (34%) were below the cut-off value for deficits in laterality recognition  
8 reaction time (3.95secs).

### 9 **3D object rotation**

10 There was a significant difference in the accuracy of mental rotation of 3D objects  
11 ( $t(62)=2.50, p=0.015$ ), with the stroke participants significantly less accurate than the  
12 control participants (stroke:  $46\% \pm 16\%$ ; control:  $56\% \pm 14\%$ ). Three participants  
13 (9.4%) in the stroke group were below the 26.9% cut off score for deficits in the  
14 mental rotation of 3D objects.

### 15 **Attention**

16 Fifteen (47%) stroke participants but none of the 36 control participants had a 99.9%  
17 confidence index for fitting a clinical profile for attention deficits on the CCPT. There  
18 was a significant difference in reaction times in the attention test, ( $t(50)=3.43,$   
19  $p=0.001$ ), with people with a stroke having significantly longer reaction times ( $531\text{ms}$   
20  $\pm 121\text{ms}$ ) than control participants ( $444\text{ms} \pm 78\text{ms}$ ). Ten participants (32.2%) in the  
21 stroke group had reaction times above the cut-off value.

### 22 **Clinically assessed deficits**

#### 23 **Neglect**

24 Three of the people with a stroke scored above 0 on the CBS for neglect with scores  
25 of between 5 and 21. The median score for neglect was 0.

#### 26 **Function**

27 Scores on the MBI ranged from 27 to 100, with a median of 98. Fifteen people with a  
28 stroke scored 100 out of 100, indicating functional independence.

#### 29 **Other clinical deficits**

30 Six participants had documented hemianopia from the medical records. Five  
31 participants had documented dysphasia. Expressive and receptive dysphasia was

1 not recorded separately. Four participants had documented dyspraxia; all  
2 participants with dyspraxia also had dysphasia.

### 3 **Relationship with lesion location**

4 Lesion locations for individual participants with deficits in laterality recognition, and/or  
5 3D object rotation were examined. The majority of those with deficits in laterality  
6 recognition had lesions involving the parietal lobe, frontal lobe or other parts of the  
7 motor network. Participants with laterality recognition deficits had both left (n=7) and  
8 right (n=10) brain damage. Participants with deficits in 3D object rotation had lesions  
9 in fronto-parietal areas or occipital cortex on the left (n= 1) and right (n=2) sides .

### 10 **Correlations**

11 In the stroke group there was a significant correlation between accuracy and reaction  
12 times in the laterality recognition task  $R^2=0.13$ ,  $p=0.04$ , with participants that had  
13 higher accuracy also having quicker reaction times. Participants whose laterality  
14 recognition was more accurate were more accurate on 3D object rotation (table 4). In  
15 the control group this correlation was not significant  $R^2=0.10$ ,  $p=0.06$ . People with a  
16 stroke who were less accurate and slower in laterality recognition were more  
17 dependent in function (table 4).

### 18 **Relationship with other deficits**

19 The participants with dyspraxia were significantly less accurate in laterality  
20 recognition ( $p=0.03$ ). There were no significant differences in people with and  
21 without neglect, hemianopia or dysphasia. Only 1 of the 6 people with a hemianopia  
22 showed a deficit in object rotation, 1 showed impaired laterality recognition accuracy  
23 and 2 showed an impaired laterality recognition reaction time.

### 24 **Discussion**

25 In keeping with previous work laterality recognition deficits were present ~33% of  
26 people post stroke [4, 12-14, 19]. Reaction times for laterality recognition showed a  
27 faster response time when recognising pictures of the dominant hand in both the  
28 stroke group and the control group [23, 28, 29] possibly reflecting differences in the  
29 efficiency of planning/ imagining dominant as opposed to non-dominant hand  
30 movements.

1 There was no significant difference in people with a stroke in terms of their accuracy  
2 or reaction times for recognising pictures of their affected vs. unaffected hand,  
3 although response time to the affected hand were longer. Daprati et al (2010)  
4 showed that patients with left brain damage with severe motor impairment were  
5 significantly slower recognising their affected hand but were also slower than  
6 controls when recognising their unaffected hand. This is felt to reflect difficulties in  
7 planning and producing movements of the affected hand. The lack of difference  
8 between recognising pictures of the affected vs. unaffected hand in the present study  
9 could be due to the broad inclusion criteria as 15 people with a stroke scored 100 on  
10 the MBI and therefore were completely independent. Without a specific measure for  
11 motor impairment of the upper limb, such as the Fugl-Meyer test, correlations  
12 between the severity of motor impairment and differences between affected and  
13 unaffected limb cannot be determined.

14 The current study did not find a difference between laterality recognition between  
15 participants with LBD or RBD. Seven of the 17 participants with deficits in laterality  
16 recognition had LBD and 10 had RBD. Daprati et al (2011) found that participants  
17 with RBD were less accurate in laterality recognition tasks; however Schwoebel and  
18 Coslett (2005) also found that deficits in laterality recognition were not specific to  
19 LBD or RBD. Schwoebel and Coslett (2005) used similar inclusion criteria to the  
20 current study, ie not based on behavioural criteria or lesion location.

21 The primary aim of this study was to explore factors that could possibly explain any  
22 differences in laterality recognition seen in the stroke group. People with a stroke  
23 were significantly less accurate in the ability to mentally rotate 3D objects. These  
24 results need to be interpreted with caution as accuracy levels were close to chance  
25 (i.e. 50%) for both groups suggesting the task had a floor effect. This may reflect  
26 task difficulty and an age-related decline in their mental rotation ability [30]. Age was  
27 significantly correlated with object rotation accuracy in both the control ( $R^2=0.23$ ,  
28  $p=0.004$ ) and the stroke group ( $R^2=0.14$ ,  $p=0.048$ ). Gender differences have also  
29 been shown on tasks involving the mental rotation of 3D objects, with males more  
30 accurate than females [31]. There was a significant gender difference between the  
31 control group and the stroke group with the control group having more females than  
32 males, which could have impacted on the slower rotation seen in the stroke

1 group. Females in the control group had an average of 50% accuracy on mental  
2 rotation of 3D objects, and males had an average of 65%.

3 The accuracy of laterality recognition was significantly correlated with accuracy of 3D  
4 object rotation as previously reported [4]. However, Tomasino et al (2003ab) showed  
5 a double dissociation with laterality recognition accuracy and 3D object rotation,  
6 suggesting that there are separate neural correlates for visual and motor imagery[16,  
7 18]. One explanation is that participants used different strategies to solve the  
8 laterality recognition task. Curtze et al (2010) suggested that upper limb amputees  
9 may use a visual transformation of the stimuli rather than motor imagery, especially  
10 when the motor imagery strategy was more difficult [23] The visual strategy to solve  
11 the hand laterality task is slower [32] and therefore if participants were using a visual  
12 strategy they would have longer reaction times and be more likely to be identified as  
13 having a deficit in laterality recognition. This may explain the weak association  
14 between the two impairments in the current study.

15 There was a correlation between laterality recognition and functional ability.  
16 However, this study does not show that the relationship is causative. Future work  
17 should assess whether laterality recognition can be trained in people with a stroke  
18 and whether this results in an improvement in hand function. To date paradigms are  
19 available for training people to recognise hand laterality in other patient groups (eg  
20 Chronic regional pain syndrome[24]) and these may be adopted as part of a future  
21 clinical trial.

## 22 Study Limitations

23 The tests were performed in a set order. This may mean that the later tests (eg 3D  
24 object rotation) may be subject to cognitive fatigue. Cognitive fatigue may be greater  
25 in people with stroke and therefore accentuate differences between the stroke and  
26 control groups. People with stroke were recruited over a long time frame (2-135  
27 days). This covers a period where marked improvements in impairments and  
28 functional ability can occur due to factors such as resolution of oedema and adaptive  
29 changes. Future work could assess longitudinal changes in laterality recognition or  
30 assess groups of people at more discrete time periods post stroke to ascertain the  
31 natural recovery of this impairment. Other impairments seemed to be associated with  
32 a higher incidence of hand laterality deficits. Clinically defined dyspraxia was

1 associated with a deficit in laterality recognition whilst 2 out of 3 participants  
2 behavioural neglect had a laterality deficit. Both of these impairments affect systems  
3 involved in sensori-motor planning. More in depth, objective, screening of these  
4 impairments is required to further explore these relationships in the future.

## 5 Conclusion

6 Implicit motor imagery, as assessed by the accuracy and speed of laterality  
7 recognition task was affected in ~33% of patients after acute stroke. Laterality  
8 recognition deficits were related to impaired mental rotation of 3D objects and  
9 dyspraxia. There was a correlation between deficits in laterality recognition and  
10 function.

11

12

## 13 Acknowledgements

14 We would like to thank the Neuro Orthopaedic Institute for the use of the recognize  
15 program for this study

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## References

1. Donnan GA, Fisher M, Macleod M, Davis SM. Stroke. *Lancet* 2008;371(9624):1612-23.
2. Aziz NA, Leonardi-Bee J, Phillips M, Gladman JR, Legg L, Walker MF. Therapy-based rehabilitation services for patients living at home more than one year after stroke. *Cochrane Database Syst Rev* 2008(2):CD005952.
3. Kwakkel G, Kollen BJ, van der Grond J, Prevo AJ. Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke. *Stroke* 2003;34(9):2181-2186.
4. de Vries S, Tepper M, Otten B, Mulder T. Recovery of motor imagery ability in stroke patients. *Rehabil Res Pract* 2011;2011:283840.
5. Barclay-Goddard RE, Stevenson TJ, Poluha W, Thalman L. Mental practice for treating upper extremity deficits in individuals with hemiparesis after stroke. *Cochrane Database Syst Rev* 2011(5):CD005950.
6. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. *Lancet Neurol* 2009;8(8):741-54.
7. Zimmermann-Schlatter A, Schuster C, Puhan MA, Siekierka E, Steurer J. Efficacy of motor imagery in post-stroke rehabilitation: a systematic review. *J Neuroeng Rehabil* 2008;5:8.
8. Sharma N, Pomeroy VM, Baron JC. Motor imagery: a backdoor to the motor system after stroke? *Stroke* 2006;37(7):1941-52.



9. Moseley GL, Sim DF, Henry ML, Souvlis T. Experimental hand pain delays recognition of the contralateral hand--evidence that acute and chronic pain have opposite effects on information processing? *Brain Res Cogn Brain Res* 2005;25(1):188-94.
10. Parsons LM. Imagined spatial transformation of one's body. *J Exp Psychol Gen* 1987;116(2):172-91.
11. Parsons LM. Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *J Exp Psychol Hum Percept Perform* 1994;20(4):709-30.
12. Vromen A, Verbunt JA, Rasquin S, Wade DT. Motor imagery in patients with a right hemisphere stroke and unilateral neglect. *Brain Inj* 2011;25(4):387-93.
13. Daprati E, Nico D, Duval S, Lacquaniti F. Different motor imagery modes following brain damage. *Cortex* 2010;46(8):1016-30.
14. Conson M, Sacco S, Sara M, Pistoia F, Grossi D, Trojano L. Selective motor imagery defect in patients with locked-in syndrome. *Neuropsychologia* 2008;46(11):2622-8.
15. Schwoebel J, Friedman R, Duda N, Coslett HB. Pain and the body schema: evidence for peripheral effects on mental representations of movement. *Brain* 2001;124(Pt 10):2098-104.
16. Tomasino B, Toraldo A, Rumiati RI. Dissociation between the mental rotation of visual images and motor images in unilateral brain-damaged patients. *Brain Cogn* 2003;51(3):368-71.

17. Tomasino B, Rumiati RI. Effects of strategies on mental rotation and hemispheric lateralization: neuropsychological evidence. *J Cogn Neurosci* 2004;16(5):878-88.
18. Tomasino B, Rumiati RI, Umilta CA. Selective deficit of motor imagery as tapped by a left-right decision of visually presented hands. *Brain Cogn* 2003;53(2):376-80.
19. Johnson SH. Imagining the impossible: intact motor representations in hemiplegics. *Neuroreport* 2000;11(4):729-32.
20. Coslett HB. Evidence for a disturbance of the body schema in neglect. *Brain Cogn* 1998;37(3):527-44.
21. de Vries S, Mulder T. Motor imagery and stroke rehabilitation: a critical discussion. *J Rehabil Med* 2007;39(1):5-13.
22. Kosslyn SM, DiGirolamo GJ, Thompson WL, Alpert NM. Mental rotation of objects versus hands: neural mechanisms revealed by positron emission tomography. *Psychophysiology* 1998;35(2):151-61.
23. Curtze C, Otten B, Postema K. Effects of lower limb amputation on the mental rotation of feet. *Exp Brain Res* 2010;201(3):527-34.
24. Moseley GL. Graded motor imagery is effective for long-standing complex regional pain syndrome: a randomised controlled trial. *Pain* 2004;108(1-2):192-8.
25. Shepard RN, Metzler J. Mental rotation of three-dimensional objects. *Science* 1971;171(3972):701-3.

26. Azouvi P, Olivier S, de Montety G, Samuel C, Louis-Dreyfus A, Tesio L. Behavioral assessment of unilateral neglect: study of the psychometric properties of the Catherine Bergego Scale. *Arch Phys Med Rehabil* 2003;84(1):51-7.
27. Shah S, Vanclay F, Cooper B. Improving the sensitivity of the Barthel Index for stroke rehabilitation. *J Clin Epidemiol* 1989;42(8):703-9.
28. Reinersmann A, Haarmeyer GS, Blankenburg M, Frettloh J, Krumova EK, Ocklenburg S, Maier C. Left is where the L is right. Significantly delayed reaction time in limb laterality recognition in both CRPS and phantom limb pain patients. *Neurosci Lett* 2010;486(3):240-5.
29. Nico D, Daprati E, Rigal F, Parsons L, Sirigu A. Left and right hand recognition in upper limb amputees. *Brain* 2004;127(Pt 1):120-32.
30. Devlin AL, Wilson PH. Adult age differences in the ability to mentally transform object and body stimuli. *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn* 2010;17(6):709-29.
31. Neubauer AC, Bergner S, Schatz M. Two- vs. three-dimensional presentation of mental rotation tasks: Sex differences and effects of training on performance and brain activation. *Intelligence* 2010;38(5):529-539.
32. Corradi-Dell'Acqua C, Tomasino B, Fink GR. What is the position of an arm relative to the body? Neural correlates of body schema and body structural description. *J Neurosci* 2009;29(13):4162-71.