University of Zurich[UZH]

Zurich Open Repository and Archive
University of Zurich
Main Library
Strickhofstrasse 39
CH-8057 Zurich
www.zora.uzh.ch

Year: 2013

Does thumb posture influence the mental rotation of hands?

Bläsing, B ; Brugger, P ; Weigelt, M ; Schack, T

Abstract: The function of thumb posture in mental rotation has not yet been studied intensely, despite its special role in manual action. To investigate if thumb posture modifies relative visual and proprioceptive contributions, we conducted two experiments comprising hand laterality judgement tasks with identical stimuli (left and right hands in palmar and dorsal views presented at four orientations). In half of the stimuli, all digits were extended, whereas in the other half the thumb was flexed into the palm of the hand. In the second experiment, participants' thumbs were taped in the same flexed posture that was displayed in half of the stimuli one hour previous to and throughout the experiment. Results of both experiments revealed effects of orientation, side and view on reaction time, but an effect of stimulus thumb posture occurred only in the second experiment in which participants' thumbs were fixed. In palmar view, stimuli rotated by 90° with fingers pointing toward the participant's midline had shorter reaction times than stimuli rotated (evidentially less comfortably) in the opposite direction. This finding suggests that participants applied motor imagery strategies for palmar but not for dorsal views of the hand, indicating a difference in visual and sensorimotor familiarity.

DOI: https://doi.org/10.1016/j.neulet.2012.11.034

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-68370
Journal Article
Accepted Version

Originally published at:
Bläsing, B; Brugger, P; Weigelt, M; Schack, T (2013). Does thumb posture influence the mental rotation of hands? Neuroscience Letters, 534(8):139-144.
DOI: https://doi.org/10.1016/j.neulet.2012.11.034

Neuroscience Letters 534 (2013): 139-144

Does thumb posture influence the mental rotation of hands?

Bettina Bläsing[a,b,*], Peter Brugger[c], Matthias Weigelt[d], Thomas Schack[a,b]

[a] Neurocognition and Action Research Group, Department of Sport Science, Faculty of Psychology and Sport Science, Bielefeld University, Universitätsstrasse 25, 33615 Bielefeld, Germany
[b] Center of Excellence Cognitive Interaction Technology, Bielefeld University, Universitätsstrasse 25, 33615 Bielefeld, Germany
[c] Neuropsychology Unit, Department of Neurology, University Hospital Zurich, 8091 Zurich, Switzerland
[d] Sport Psychology Unit, Department of Sports and Health, Faculty of Science, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany
* Corresponding author at: Neurocognition and Action Research Group, Faculty of Psychology and Sport Science and Center of Excellence Cognitive Interaction Technology, Universitätsstrasse 25, 33615 Bielefeld, Germany ; Phone: +49-521-106-5137 ; Fax: +49-521-106-6432; Email: bettina.blaesing@uni-bielefeld.de (Bettina Bläsing)

Contributions:
The study was planned and initiated by Bettina Bläsing, Peter Brugger and Thomas Schack and carried out by Bettina Bläsing and Matthias Weigelt at the laboratory of Thomas Schack.

Abstract

The function of thumb posture in mental rotation has not yet been regarded intensely, despite of the specific role of the thumb in manual action. To investigate whether thumb posture would modify the relative visual and proprioceptive contributions, we conducted two experiments with identical stimuli (left and right hands in palmar and dorsal views presented at four orientations) in which participants were asked to give handedness judgements. In half of the stimuli, the thumb was extended like the other digits, in the other half the thumb was flexed into the palm of the hand. In the second experiment, the participant's thumbs were fixed in the same posture as displayed in half of the stimulus pictures; thumbs were taped to the palm of the hands one hour previous to and throughout the experiment. Results of both experiments revealed effects of orientation, side and view on reaction time, but an effect of stimulus thumb posture occurred only in the second experiment in which the participants' thumbs were fixed. Medial-over-lateral advantage as indicator of motor imagery was found only for palmar stimuli, suggesting that participants applied different strategies for the different views of the hand, probably based on different visual and sensorimotor familiarity.

Introduction

Mental rotation of human body parts, especially hands, has been found to differ essentially from mental rotation of abstract objects [13,17]. Using a handedness paradigm in which participants had to decide if a displayed hand was a right or left one, Parsons [13,14] showed that RTs were not only influenced by the rotation angle of the hand stimulus but also by the implicit awkwardness of the displayed hand position. He concluded that movements performed mentally would induce motor imagery and would therefore be constrained by anatomical joint characteristics in a similar way as real movements [14]. The use of motor imagery strategies in mental rotation of hands has been corroborated by many authors [e.g., 9,14,23]. Evidence for motor imagery being involved in mental rotation of body parts comes from clinical cases [e.g., 3,4,12,16] and from neuroimaging studies (see [22] for review). Further studies proposed that mental rotation tasks can be solved by different strategies, involving visual imagery or motor imagery [2,11], and that the choice of strategy might depend on the type of stimuli [21] or the instructions [20].

One argument that has been brought forward in favour of a motor imagery strategy is the posture effect. Several studies showed that the posture the participant's hand is adopting during the experimental task also influences the processing of handedness decisions. Early on, Parsons [14] demonstrated an effect of hand posture on handedness judgements. Sirigu and Duhamel [18] showed an inhibiting influence of hand position on body part imagery in an egocentric first person perspective. Mental rotation of hands, but not feet, was found to be slower when the participants were keeping their hands behind their backs with interleaved fingers than when their hands were placed on their knees [9]. The authors argued that current hand posture should influence limb-specific laterality decisions via the body schema in a bottom-up manner.

Previous mental rotation studies have only paid little attention to the role of the thumb as a special digit of the human hand. This is surprising, given the special role of the thumb in human hand anatomy and hand function [e.g., 6,7,8,15]. Several studies pointed towards the significance of the thumb as asymmetry marker in handedness tasks if visual strategies are applied [e.g.,19,20]. For motor strategies, the role of the thumbs has so far not been investigated. In the present study, we investigated the influence of thumb posture on performance in a handedness judgment task. Thumb posture was modified in the stimulus images (visual influence) as well as in the participants' hands (sensorimotor influence). Two experiments were conducted with the same stimulus pictures of hands in which thumb posture was varied in such a way that the thumb was either extended like the other digits in an open hand posture (pointing outward), or flexed into the palm of the hand (pointing inward). In the first experiment, the participants' hands were unrestricted, whereas in the second experiment, the participants' thumbs were fixed to the palm of the hand in a position corresponding to that displayed in one half of the stimulus pictures. We expected that under normal (i.e., unrestricted) conditions the stimulus pictures with extended thumbs pointing outward would be easier to process than the ones with flexed thumbs, due to their clearer and more typical shape, resulting in shorter RTs and lower error rates. Second, we expected that this effect would be reduced by a facilitating posture effect in the second experiment in which the participants' thumbs were fixed in the flexed posture.

Experiment 1

This experiment tested the effect of two different thumb postures (extended, pointing outward vs. flexed into the palm of the hand, pointing inward) displayed in the stimulus pictures on the mental rotation of human hands.

Material and Method

Participants

Eighteen healthy right-handed participants (age 23.56 ± 2.62 years, sports science students, 15 females) participated in the experiment. Written informed consent was obtained prior to the experiment. The study was conducted in accordance with the 1964 Declaration of Helsinki.

Task and stimuli
In a response time experiment, the participants' task was to decide whether a given stimulus picture depicted a human left or right hand. The set of 32 stimuli used in this experiment consisted of colour photographs of a left or right human hand in palmar or dorsal view, with the thumb either extended like the other fingers or flexed into the palm of the hand (and hence only visible in dorsal view). The hand images were displayed in four orientations (0°, 90°M, 90°L, 180°). Stimuli were presented in nine randomised blocks, in which each stimulus was displayed once for an exposure time of 2000ms, resulting in 32 trials per block, and a total of 288 stimuli for the whole experiment.
Procedure
Participants were seated in front of a computer screen. Microbehavioural Systems Presentation software was used to control stimulus presentation and to collect responses. Participants responded to the presentation of each stimulus by pressing one of two defined keys on the computer keyboard with their left or right index finger in order to indicate if the stimulus was a right or left hand.
Data analysis
We measured error rates and response times (RT). Error rates were defined as number of incorrect responses, regardless of RT, and analysed using Friedman tests and Wilcoxon signed-rank tests. RT was measured as time between stimulus onset and key press, as measured by the Presentation software protocol. For the analysis of RTs, only correct trials with RTs between 500ms and 3500ms were regarded. RTs were analyzed using repeated measures analysis of variance (ANOVA) with main factors THUMB posture (inward, outward), VIEW (dorsal, palmar), SIDE (left, right) and orientation ANGLE (0°, 90°M, 90°L, 180°). The finding that hands pointing in medial direction with their fingers commonly required shorter RTs than hands pointing in lateral direction [e.g., 14] has been described as medial-over-lateral-advantage (MOLA, [5]). We calculated MOLA by comparing RTs of medial and lateral orientations directly using repeated measures ANOVA with factors THUMB, VIEW, SIDE and ANGLE on the data of 90°M and 90°L orientations. In total, 5760 trials were recorded. For the analysis of RT, 654 trials were disregarded due to incorrect answers and 64 trials due to aberrant RTs (33 <500ms, 31 >3500ms). Finally, 87.5% of the total number of trials were included in the analysis of RT.

Results
Error rates
Error rates for corresponding stimuli (left/ right hand, thumbs inward/ outward, dorsal/ palmar view) were compared using Wilcoxon signed-rank tests. No differences occurred between corresponding left and right stimuli and stimuli with thumbs pointing inward vs. outward. Significant differences were found for corresponding stimuli of different views presented at 0° and 90°L orientations (exception: 0° left outward), showing that stimuli in palmar view had higher error rates than stimuli in dorsal view. Finally, error rates for the different orientation angles were compared within each thumb position, side and view using Friedman tests. Differences between orientation angles were found for all stimuli in dorsal view (right inward: $\chi_2(3)=22.795$, $p<0.001$; left inward: $\chi_2(3)=11.686$, $p<0.01$; right outward: $\chi_2(3)=17.452$, $p<0.01$; left outward: $\chi_2(3)=12.157$, $p<0.01$). Post-hoc Wilcoxon signed-rank tests revealed that, in dorsal view, 180° stimuli had higher error rates than stimuli presented at 0°, 90°M and 90°L for both sides and both thumb postures (for detailed results see Table 1).
Reaction times
The results of the first ANOVA (2x2x2x4) revealed effects of SIDE ($F[1, 19]=12.160$; $p<.01$; partial $\eta_2=0.390$; Mean right: 1228, left: 1276), ANGLE ($F[2.135, 40.559]=40.824$; $p<.001$; part. $\eta_2=0.682$; Mean 0°: 1138, 90°M: 1131, 90°L: 1331, 180°: 1432) and VIEW ($F[1, 19]=51.670$; $p<.001$; part. $\eta_2=0.7131$; Mean dorsal: 1108, palmar: 1409), and an interaction between VIEW and ANGLE ($F[2.245, 42.663]=19.394$; $p<.001$; part. $\eta_2=0.505$), but no effect of THUMB (Mean inward: 1262, outward: 1242) Mauchly's test showed that the assumption of sphericity was violated for ANGLE ($X_2(5)=11.476$; $p<0.05$) and for VIEW*ANGLE ($X_2(5)=11.749$; $p<0.05$), therefore the degrees of freedom were corrected for the estimation of

sphericity (Greenhouse-Geisser, ANGLE: e=0.712, VIEW*ANGLE: e=0.748). Post-hoc pairwise
comparison (Bonferroni adjusted) revealed differences for ANGLE between 0° and 90°L, 0° and 180°, 90°M and 90°L, and 90°M and 180° (all $p<.001$). Means of the RTs are shown in Figure 1.
The results of the second ANOVA (2x2x2x2, MOLA) revealed main effects for VIEW ($F[1, 19]=42.66$; $p<.001$; partial $\eta^2=0.692$; Mean dorsal: 1076, palmar: 1400), SIDE ($F[1, 19]=8.98$; $p<.01$; partial $\eta^2=0.321$; Mean right: 1197, left: 1261) and ANGLE ($F[1, 19]=40.97$; $p<.001$; partial $\eta^2=0.683$; Mean 90°M: 1131, 90°L: 1331), and interactions between THUMB and ANGLE ($F[1, 19]=5.013$; $p<.05$; partial $\eta^2=0.209$) and VIEW and ANGLE ($F[1, 19]=15.162$; $p<.01$; partial $\eta^2=0.444$), but no effect of THUMB (Mean inward: 1242, outward: 1216) Paired samples t-tests revealed differences between 90°M and 90°L for stimuli in palmar view (right inward: $t(19)=-4.476$, $p<0.001$; left inward: $t(19)=-4.481$, $p<0.001$; right outward: $t(19)=-4.539$, $p<0.001$; left outward: $t(19)=-6.072$, $p<0.001$), but not for stimuli in dorsal view (a tendency occurred for outR: $t(19)=-2.093$, $p=0.05$;).

=== insert Figure 2 about here ===

Experiment 2
The second experiment examined the effect of restricting the thumbs by fixating them to the palms of participants' hands on the mental rotation performance of human hands with varying thumb postures.

Material and Method
Participants
Eighteen healthy right-handed participants (age 24.17 ± 4.53 years, sports science students, 16 females) participated in this experiment; none of them had previously taken part in Experiment 1. Written informed consent was obtained prior to the experiment. The study was conducted in accordance with the 1964 Declaration of Helsinki.
Task and stimuli, procedure, and data analysis
Participants carried out the same task as in the previous experiment. The same stimuli were used and presented in exactly the same way as in Experiment 1. The only difference in the procedure was that the participants' thumbs were taped into the palms of their hands one hour prior to the start of the experiment. The experimenter wrapped adhesive tape around the participant's hands held in a posture with the thumb flexed into the palm, fixating them in the same position as displayed in half of the stimulus pictures, where remained throughout the experiment. During the hour between taping and the start of the experiment, participants were allowed to carry on with their everyday activities, which were in most cases eating and drinking, reading in the library, and working on the computer.
Data were analysed in the same way as for Experiment 1. In total, 5760 trials were recorded. For the analysis of RT, 705 trials were disregarded due to incorrect answers and 66 trials due to aberrant RTs (27 <500ms, 39 >3500ms). Finally, 86.6% of the total number of trials was included in the analysis.

Results
Error rates
Error rates for corresponding stimuli (left/ right, inward/ outward, dorsal/ palmar) were compared using Wilcoxon signed-rank tests. No differences between corresponding left and right stimuli were found except for stimuli with thumbs pointing inward in dorsal view at 180° orientation (error rates were higher for right stimuli). Differences between corresponding stimuli with different thumb postures were found only for left stimuli in palmar view at 0° and 90°L orientations (error rates were higher for thumbs pointing inward). Differences between stimuli displayed in different views were found for 0°, 90°M and 90°L orientations (exception: 90°M left outward), with higher error rates occurring for stimuli in palmar view. Finally, error rates for the different orientation angles were compared within each thumb position, side and view using Friedman tests. Differences between orientation angles were found for all stimuli

in dorsal view (right inward: $\chi_2(3)=41.069$, $p<0.001$; left inward: $\chi_2(3)=15.024$, $p<0.01$; right outward: $\chi_2(3)=34.178$, $p<0.001$; left outward: $\chi_2(3)=15.692$, $p<0.01$) and for left stimuli with thumbs pointing inward in palmar view ($\chi_2(3)=15.933$, $p<0.01$). Post-hoc Wilcoxon signedrank
tests revealed that, in dorsal view, 180° stimuli had higher error rates than stimuli presented at 0°, 90°M and 90°L for both sides and both thumb postures. In palmar view, left hand stimuli with thumbs pointing inward had higher error rates in 90°L orientation than in 90°M and 180° stimuli and in 90°M orientation than in 0° orientation (for detailed results see Table 1).

=== insert Table 1 about here ===

Reaction times

The results of the first ANOVA (2x2x2x4) revealed effects of SIDE ($F[1, 19]=17.826$; $p<.001$; partial $\eta_2=0.484$; Mean right: 1269, left: 1362), THUMB ($F[1, 19]=13.958$; $p<.01$; part. $\eta_2=0.424$; Mean inward: 1337, outward: 1293), ANGLE ($F[3, 57]=42.587$; $p<.001$; part. $\eta_2=0.691$; Mean 0°: 1185, 90°M: 1195, 90°L: 1399, 180°: 1507) and VIEW ($F[1, 19]=33.848$; $p<.001$; part. $\eta_2=0.640$; Mean dorsal: 1183, palmar: 1460), and an interaction between VIEW and ANGLE ($F[2.030, 38.570]=44.115$; $p<.001$; part. $\eta_2=0.699$). Mauchly's test revealed that the assumption of sphericity was violated for VIEW*ANGLE ($X_2(5)=14.929$; $p<0.05$), therefore the degrees of freedom were corrected (Greenhouse-Geisser, $e=0.677$). Post-hoc pair-wise comparison (Bonferroni adjusted) revealed differences for ANGLE between 0° and 90°L, 0° and 180°, 90°M and 90°L, and 90°M and 180° (all $p<.001$). Means of RTs are shown in Figure 2.
The results of the second ANOVA (2x2x2x2; MOLA) revealed main effects for THUMB ($F[1, 19]=7.097$; $p<.05$; partial $\eta_2=0.272$; Mean inward: 1307, outward: 1276), VIEW ($F[1, 19]=39.396$; $p<.001$; partial $\eta_2=0.675$; Mean dorsal: 1132, palmar: 1475), SIDE ($F[1, 19]=11.343$; $p<.01$; partial $\eta_2=0.374$; Mean right: 1244, left: 1339) and ANGLE ($F[1, 19]=45.374$; $p<.001$; partial $\eta_2=0.705$; Mean 90°M: 1195, 90°L: 1399), and an interaction between VIEW and ANGLE ($F[1, 19]=16.886$; $p<.01$; partial $\eta_2=0.471$). Paired samples ttests revealed differences between 90°M and 90°L for stimuli in palmar view (right inward: $t(19)=-6.091$, $p<0.001$; left inward: $t(19)=-4.673$, $p<0.001$; right outward: $t(19)=-5.280$, $p<0.001$; left outward: $t(19)=-5.695$, $p<0.001$). For stimuli in dorsal view, a difference occurred only for inL ($t(19)=-2.824$, $p<0.05$;).

=== insert Figure 2 about here ===

Discussion

We had expected that stimulus images of hands with the thumb extended in an open hand position like the other digits would generally be processed faster than those with the thumb flexed into the palm. In Experiment 1, in which the participants' thumbs were unrestricted, no effect of stimulus thumb posture was observed, indicating that hands with the thumb extended and hands with the thumb flexed were processed with similar accuracy and speed. In contrast, in Experiment 2, the expected effect of stimulus thumb posture on RTs was found, indicating that participants under this condition processed stimuli with outstretched thumbs quicker than stimuli with the thumb flexed into the palm. The modified proprioceptive feedback from the participants' fixed thumbs apparently influenced the processing of handedness judgements, but not in terms of a typical posture effect. As RTs for stimuli with flexed thumbs required longer RTs under this condition, the results suggest that the participants' hand posture did not facilitate the handedness judgement for stimuli with corresponding posture but rather interfered with it. We could speculate that the adaptation time of one hour prior to the experiment might have been too short for the participants to really adapt to their new thumb posture to perceive it as "normal". A longer preparation time with a fixed thumb might have increased the influence of the participants' own hand posture, potentially eliciting a stronger posture effect. This assumption, however, is contradicted by the finding that in studies in which a posture effect was observed, no adaptation time was

applied previous to the experiment, but the posture was adopted only during the experiment [9,10].
In both experiments, medial-over-lateral-advantage (MOLA) was found regularly for stimuli in palmar view, but not for stimuli in dorsal view. MOLA has been regarded as typical indicator of motor imagery being applied to solve handedness tasks [5]. Therefore, this finding can be interpreted as pointing towards a general difference between the processing of palmar and dorsal hand stimuli. Ionta and Blanke [10] had found an effect of stimulus orientation only in dorsal view, and concluded that uncommon views (such as the palmar one) should be less sensitive to orientation changes. The results suggest that palmar hand stimuli were processed using a motor strategy, whereas dorsal stimuli were processed using a visual strategy. As participants were not explicitly instructed to use the thumb as cue, using a visual strategy, they could have spontaneously adopted such a mixed strategy to solve the task [see 11,20]. This interpretation contradicts the claim that motor imagery strategies were applied if mental rotation of the presented stimuli involved more than one rotational axis [19]. The finding of different strategies being applied to dorsal and palmar stimuli could partly be based on differences in the familiarity of different hand views; looking at one's own hand in palmar view seems to be more common than in dorsal view, whereas other's hands are more commonly observed in dorsal view. The palmar view might be less commonly visually observed, but might correspond more strongly to the experienced own hand in action (especially in medial orientation) and thereby rather evoke motor imagery.
An additional aspect regarding the difference between palmar and dorsal views is that in our stimulus pictures the visibility of the thumb in flexed posture clearly depended on the view. In palmar view, the thumb was clearly visible lying in the palm of the hand, and this unusual thumb posture might have been perceived as awkward or visually less familiar than in the extended position, and might therefore have interfered with mental processing. In dorsal view, the flexed thumb was hidden behind the hand, and participants might have ignored or added it mentally to complete the familiar hand image [see 1].
To conclude, fixing the participants' thumbs in the same posture as presented in half of the stimulus pictures resulted in an effect of stimulus thumb posture that had not been observed in the participants with unrestricted thumbs, showing that RTs were longer for the congruent flexed thumb posture. This finding suggests that the modified proprioceptive feedback from the participants' own fixed thumbs influenced the processing of handedness judgements. As the fixed thumb posture did not facilitate handedness judgements but rather impeded them, the results can not be interpreted as common posture effect. In both experiments, MOLA was found for palmar stimuli but not for dorsal stimuli, suggesting that participants applied different strategies for the different views of the hand, probably based on different visual and sensorimotor familiarity.

References

[1] B. Bläsing, M. de Castro Campos, T. Schack, P. Brugger, Mental rotation of primate hands: human-likeness and thumb saliency, Exp. Brain Res. (2012) 93-105.
[2] C. Corradi-Dell'acqua, B. Tomasino, G.R. Fink, What is the position of an arm relative to the body? Neural correlates of body schema and body structural description, J. Neurosci. 29(13) (2009) 4162-4171.
[3] M. Fiorio, M. Tinazzi, S.M. Aglioti, Selective impairment of hand mental rotation in patients with focal hand dystonia, Brain 129(Pt 1) (2006) 47-54.
[4] M. Fiorio, M. Tinazzi, S. Ionta, A. Fiaschi, G. Moretto, M.J. Edwards, K.P. Bhatia, S.M. Aglioti, Mental rotation of body parts and non-corporeal objects in patients with idiopathic cervical dystonia, Neuropsychol. 45 (2007) 2346-2354.
[5] M. Funk, P. Brugger, Mental rotation of congenitally absent hands, J. Int. Neuropsychol. Soc. 14(1) (2008) 81-89.
[6] C. Häger-Ross, M.H. Schieber, Quantifying the independence of human finger movements: comparisons of digits, hands, and movement frequencies, J. Neurosci. 20 (2000) 8542-8550.
[7] T. Imaeda, K.N. An, W.P. Cooney, Functional anatomy and biomechanics of the thumb, Hand Clin. 8 (1992) 9-15.

[8] J.N. Ingram, K.P. Koerding, I.S. Howard, D.M. Wolpert, The statistics of natural hand movement, Exp. Brain Res. 188 (2008) 223-236.
[9] S. Ionta, A. Fourkas, M. Fiorio, S.M. Aglioti, The influence of hands posture on mental rotation of hands and feet, Exp. Brain Res. 183 (2007) 1-7
[10] S. Ionta, O. Blanke, Differential influence of hands posture on mental rotation of hands and feet in left and right handers, Exp. Brain Res. 195 (2009) 207-217.
[11] S.M. Kosslyn, G.J. Di Girolamo, W.L. Thompson, N.M. Alpert, Mental rotation of objects versus hands: neural mechanisms revealed by positron emission tomography, Psychophysiol. 35(2) (1998) 151-161.
[12] G.L. Moseley, Why do people with complex regional pain syndrome take longer to recognize their affected hand? Neurology 62 (2004) 2182-2186.
[13] L.M. Parsons, Imagined spatial transformations of one's hands and feet, Cogn. Psychol. 19 (1987) 178-241.
[14] L.M. Parsons, Temporal and kinematic properties of motor behavior reflected in mentally simulated action, J. Exp. Psychol. Hum. Percept. Perform. 20(4) (1994) 709-730.
[15] K.T. Reilly, G.R. Hammond, Independence of force production by digits of the human hand, Neurosci. Lett. 290 (2000) 53-56.
[16] J. Schwoebel, R. Friedman, N. Duda, H.B. Coslett, Pain and the body schema: evidence for peripheral effects on mental representations of movement, Brain 124 (2001) 2098-2104.
[17] K. Sekiyama, Kinesthetic aspects of mental representations in the identification of left and right hands, Percept. Psychophys. 32(2) (1982) 89-95.
[18] A. Sirigu, J.R. Duhamel, Motor and visual imagery as two complementary but neurally dissociable mental processes, J. Cogn. Neurosci. 13(7) (2001) 910-919.
[19] A.C. Ter Horst, R. van Lier, B. Steenbergen, Mental rotation task of hands: Differential influence number of rotational axes, Exp. Brain Res. 203(2) (2010) 347-354.
[20] B. Tomasino, R.I. Rumiati, Effects of strategies on mental rotation and hemispheric lateralization: Neuropsychological evidence, J. Cogn. Neurosci. 16 (2004) 878-888.
[21] B. Tomasino, A. Toraldo, R.I. Rumiati, Dissociation between the mental rotation of visual images and motor images in unilateral brain-damaged patients, Brain Cogn. 51 (2003) 368-371.
[22] J.M. Zacks, Neuroimaging studies of mental rotation: a meta-analysis and review, J. Cogn. Neurosci. 20 (2008) 1-19.
[23] A. Wohlschläger, A. Wohlschläger, Mental and manual rotation, J. Exp. Psych. Hum. Percept. Perform. 24 (1998) 397–412.