

# Children's left parietal brain activation during mental rotation is reliable as well as specific

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## Abstract

Some recent evidence suggests that mental rotation of characters in children aged 7 or 8 years might be lateralized to the left parietal hemisphere. An alternative statement exists, however, the finding might be completely unspecific for mental rotation but either be simply a function of task difficulty or a consequence of the use of characters as stimuli. To test these alternatives, ERPs of 24 second graders were measured twice: (a) during mental rotation with characters as stimuli and orientations of 30°, 90°, or 150° and (b) during memory scanning with characters as stimuli and set sizes of 1, 2, or 3 letters. In both cases, an amplitude modulation was found. The effect of mental rotation as a function of character orientation turned out to be lateralized to the left parietal hemisphere. The effect of memory scanning as a function of set size, however, turned out to be completely non-lateralized. Thus, children's left hemisphere activation during mental rotation is reliable as well as specific.

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Mental rotation refers to the cognitive process of imagining how an object would look if rotated away from the orientation in which it is actually presented (Shepard & Metzler, 1971). It constitutes an important aspect of spatial intelligence. Mental rotation seems to be a cognitive process implemented in the parietal cortex (e.g., Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001) that is working in a continuous, analog way (e.g., Heil, Bajric, Rösler, & Hennighausen, 1997).

Additionally, it is generally assumed that mental rotation should be understood as a cognitive process fundamentally lateralized to the right hemisphere (for a review, see Corballis, 1997). The asymmetry seems to be critically dependent, however, upon a number of factors like subject's gender (Roberts & Bell, 2000), handedness (Johnson, McKenzie, & Hamm, 2002), spatial intel-

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ligence (Rösler, Heil, Pauls, Bajric, & Hennighausen, 1994), sex steroid level (McCormick & Teillon, 2001), as well as the dimensionality of the rotation (Roberts & Bell, 2003), the difficulty of the task (Corballis & McLaren, 1984), and the type of stimuli used (Desrocher, Smith, & Taylor, 1995). Additionally, the pattern of data is difficult to integrate since these factors interact in quite complex ways. So, for example whereas the right lateralization seems to be present for male subjects, female subjects show this pattern only during the menstrual phase while during the luteal phase of their menstrual cycle, no hemispheric differences were observed (see, e.g., Güntürkün & Hausmann, 2003). Right hemisphere activation, present in people with high spatial abilities, contrasted with left hemisphere activation, present in people with low spatial abilities despite equal general intelligence (Rösler et al., 1994). Whereas the right hemisphere seems to be crucial for mental rotation of (some) visual objects, the left hemisphere seems to be preferentially engaged when hands have to be mentally rotated (Tomasino, Toraldo, & Rumiati, 2003). A bilateral activation of both hemispheres, however, seems to be present when characters as stimuli are used (Heil, 2002).

Therefore, it is important that studies investigating the neural basis for mental rotation are directly linked to the mental rotation process itself. In a number of studies with adults, it was found that in a mental rotation task, the amplitude of event-related potentials (ERPs) extracted from the EEG is systematically related to the orientation of the stimulus: the stimulus-evoked positivity becomes relatively more negative (i.e., less positive) with increasing angular disparities from the upright orientation (see, e.g., Wijers, Otten, Feenstra, Mulder, & Mulder, 1989). Wijers et al. (1989) suggested that the gradual decrease of the positivity is caused by a modulation of a slow negativity that should be understood as an electrophysiological correlate of the mental rotation process itself.<sup>1</sup> If so, then a couple of predictions follow which were validated in a number of recent studies (for a review, see Heil, 2002): the mere classification of a character as a digit or a letter is executed without mental rotation (Corballis & Nagourney, 1978) and accordingly, Heil, Bajric, Rösler, and Hennighausen (1996) obtained an amplitude modulation due to character orientation in a parity judgment task which was absent in a character classification task. Moreover, the presence of the amplitude modulation should depend on whether the process of mental rotation is executed or not, but should not depend on whether the *response is executed or not*, exactly what Heil, Rauch, and Hennighausen (1998) found. Finally Heil and Rolke (2002) provided evidence that not only the process of mental rotation but also the amplitude modulation itself was delayed, when either the perceptual quality of the stimulus was reduced or when character discrimination was more difficult.

Hardly anything is known about the development of hemispheric laterality with respect to mental rotation. Recently, Jansen-Osmann and Heil (in press) presented the first study in which the well-known ERP-effect during mental rotation of characters was not only observed with adults, but also with children 11–12 years of age as well as with 7 or 8 years old children. The authors observed a developmental change in the pattern of hemispheric asymmetry of the parietal ERP effect, i.e., of the amplitude modulation as a function of character orientation. With adults, they replicated the pattern observed in earlier studies (e.g., Heil, 2002), in which a bilateral parietal amplitude modulation was only marginally lateralized to the right hemisphere. For children, especially for the second-graders, however, the results indicated a substantially greater left compared to right hemisphere amplitude modulation as a function of character orientation at parietal leads. These

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<sup>1</sup> Negativity in the slow ERP usually is understood as an increase of neural activity in the underlying cortex (Rösler, Heil, & Röder, 1997).

results suggest that the development of mental rotation should be understood as a function that becomes more and more independent of processes localized in the left hemisphere.

This conclusion was based on the amplitude modulation as a function of character orientation that turned out to be lateralized to the left hemisphere in the younger children. The more mental rotation was executed by the younger children, the more the neural activity was lateralized to the left hemisphere. These findings could be of great importance for developmental cognitive neuroscience because they might allow not only developing a model describing the development and plasticity of hemispheric asymmetry/specialization but also to test such a model experimentally. The criteria of the reliability as well as of the validity of the findings, obviously, constitute the crucial premises of this view.

Therefore, it was the first goal of our study to replicate the finding of a left lateralization of the children's ERP effect during mental rotation. The second and most important goal was to eliminate an alternative explanation concerning the specificity of the effect that would undermine the validity of the findings.

The effect was a function of the amount of mental rotation, but was it also specific for mental rotation? That is, is the left hemisphere activation indeed a consequence of mental rotation (the larger the angular disparity the more mental rotation has to be executed), or is it a consequence of simply increasing the difficulty of the task (the larger the angular disparity the more difficult the task)? The greater a character's angular disparity from the upright, the more mental rotation has to be executed but at the same time, the more difficult the task, i.e., the more (unspecific) effort has to be invested. Either the additional amount of mental rotation or the additional amount of effort might have resulted in an increasing left lateralization of children's brain activity, because both are perfectly correlated. A more specific version of this alternative interpretation would be restricted to effort and task difficulty when characters as stimuli are used. That is, whenever children work with such verbal material, increasing the difficulty of the cognitive processes involved might result in an increasing left lateralization of their cortical activity.

Obviously, an empirical test for this alternative explanation is needed. The most critical test for the assumption, in fact, has to involve, first, a difficulty manipulation with, second, characters as stimuli that results in, third, an amplitude modulation of the ERP. If this amplitude modulation were *not* to be lateralized to the left hemisphere, then the specificity of the effect would *substantially* be validated. Fortunately, Sternberg (1966) memory scanning task exactly fulfills these requirements. The difficulty of the task can be manipulated as a function of memory set size and characters can be used as stimuli. Moreover, RT data suggest that the same rate of processing speed increase as a function of age exists for mental rotation and for memory scanning (Park, 1996). Finally, increasing set size results in an amplitude modulation of the ERP that is relatively similar in latency and topography with a maximum over parietal cortex to the effect observed during mental rotation (see, e.g., Heil, Hennighausen, & Özcan, 1999). If any one version of the alternative explanations outlined above was to be correct, then the ERP effect during memory scanning should also be lateralized to the left hemisphere. However, if the left lateralization could be replicated with a mental rotation task but would be absent in the same children with a memory scanning task that both used characters as stimuli, this pattern of results would give strong support to the claim that the increase in left parietal lateralization with increasing orientation observed for children is indeed specific for the process of mental rotation.<sup>2</sup>

<sup>2</sup> Memory scanning is used as a control condition for the effects of difficulty, effort and characters as stimuli. Although the amplitude modulation for both mental rotation and memory scanning is maximal at parietal leads, we do not want to suggest that they index similar neuro-cognitive systems.

Therefore, 7 or 8 years old children came to the laboratory for two sessions. During one session, they solved a mental rotation task with characters. During the other session, they solved a memory scanning task with characters. In the mental rotation task, stimulus orientation was manipulated while in the memory scanning task, set size was manipulated. The EEG was recorded during both sessions.

## 1. Methods

### 1.1. Participants

Twenty-four second graders, 12 boys and 12 girls (mean age: 8.6 years, age range: 7.4–8.11 years), participated in this study. Prior to testing, all parents gave their informed written consent for children's participation. The local ethics committee approved the experimental procedure.

### 1.2. Material and procedure

Each child came to the laboratory for two sessions separated by approximately a week, in order to participate in the two tasks, the sequence of tasks varied across participants. Participants were instructed to respond as fast as possible, but accuracy was stressed in the instructions. Moreover, children were instructed to avoid eye and other body movements during the recording of the EEG.

In the mental rotation task, in each trial one of the letters F, P, R, and L were presented in their normal or mirror-image version at either 30°, 90°, or 150° clockwise or counterclockwise from the vertical upright on a computer screen. The letters had a height of 3.2 cm subtending 2.28° of visual angle given a viewing distance of approximately 1 m. Each trial began with the presentation of a fixation point. One second later, a letter was presented and remained visible until a button press response. Participants pressed the left or right mouse button depending on whether the letter was normal or mirror-reversed. The letter was then replaced by a “+” or “–” for 500 ms indicating the correctness of the response. Trials were separated by randomly varying intervals of 1–3 s. Letters were presented in blocks of 48 trials each. Each combination of orientation, version, and letter occurred seven times resulting in 336 experimental trials. To familiarize participants with the task, 48 unrecorded practice trials were added.

In the memory scanning task, the lower-case letters b, f, h, j, m, and z were used. Each trial began with the presentation of a fixation point. One second later, the memory set consisting of a random selection of 1, 2, or 3 letters was presented in the center of the screen for 2 s. One second later, a single probe letter was presented and remained visible until a button press indicated whether or not the probe was a member of the set. The letter was then replaced by a “+” or “–” for 500 ms indicating the correctness of the response. Trials were separated by randomly varying intervals of 1–3 s. Letters were presented in 9 blocks of 36 trials each (i.e., 324 experimental trials). To familiarize participants with the task, 36 unrecorded practice trials were added.

### 1.3. EEG analysis

The EEG was recorded monopolarly, with AgAgCl electrodes from frontal (Fz), central (Cz), and parietal (left: P3; midline: Pz; right: P4) leads and with digitally averaged earlobes as reference. We limited our study to these electrodes because former studies showed the specific mental rotation effect as well as the effect of memory scanning to be maximal at these three parietal leads (Heil, 2002; Heil et al., 1999). Horizontal and vertical eye movements were monitored by two channels.

The left mastoid served as ground. Electrode impedance was kept below 5 k $\Omega$ . Band pass was set from dc to 40 Hz; the digitization rate was 250 Hz. All trials were inspected off-line, and those contaminated with artifacts (blinks, eye or other body movements) – less than 30% on average in all conditions – were rejected. From the edited set of raw data, we extracted ERPs by averaging single trials with correct responses separately for participants, electrodes, and experimental conditions. The average amplitude of the epoch 300–700 ms after character presentation (see Heil, 2002) was used as dependent variable, referenced to a pre-stimulus baseline of 250 ms duration.<sup>3</sup> We corrected the significance levels of all analyses of variance results according to the method of Huynh and Feldt (1976) to compensate for non-sphericity of the data for the within-subject effects of orientation and set size.

## 2. Results

For all ANOVAs, gender was introduced as a between-subject effect but did not result in any reliable main effects or interaction terms (see, e.g., Desrocher et al., 1995, for the absence of gender differences in mental rotation with letters). The same holds true for the between-subject effect of sequence of tasks. Therefore, results are presented collapsed across these factors.

### 2.1. Behavioral data

In the mental rotation task, we found an effect of character orientation for RT ( $F(2, 46) = 15.36$ ) as well as for error rate ( $F(2, 46) = 12.31$ ; both  $p < .01$ ). Mean RT (1378 ms versus 1527 ms versus 1715 ms) and error rate (11.1% versus 12.5% versus 17.2%) increased with increasing angular displacement. Comparably, in the memory scanning task, RT ( $F(2, 46) = 42.53$ ;  $p < .01$ ) as well as error rate ( $F(2, 46) = 4.17$ ;  $p < .05$ ) turned out to be a function of memory set size. Mean RT (1141 ms versus 1372 ms versus 1460 ms) and error rate (6.9% versus 9.9% versus 10.7%) increased with increasing set size. Neither the increase of RT ( $F(2, 46) = 1.43$ ) nor the increase of error rate ( $F(2, 46) = 2.03$ ; both  $p > .15$ ) differed between the two tasks.

### 2.2. ERPs

For the mental rotation task, the effect of orientation was observed at all electrodes except Fz, with the most pronounced effects at parietal leads. Presentation of the character evoked a large positivity (see Fig. 1). The amplitude of the positivity decreased with increasing angular displacement ( $F(2, 46) = 22.77, 10.04, \text{ and } 12.04$ , respectively, for P3, Pz, and P4; all;  $p < .01$ ). In order to test the laterality of the orientation effect, an ANOVA was run with factors orientation and laterality (electrodes P3 versus P4). In addition to a main effect of orientation ( $F(2, 46) = 18.63$ ), a two-way interaction was found ( $F(2, 46) = 9.17$ ;  $p < .01$ ), indicating the fact that the amplitude modulation as a function of character orientation was substantially lateralized to the left parietal lead (see Fig. 2).

For the memory scanning task, the effect of set size was found reliably at all electrodes, with the most pronounced effects at parietal leads. Presentation of the character evoked a positivity

<sup>3</sup> A more fine grained temporal analysis, in fact, does not change the pattern of results. The set size effect turned out to be reliable in the time range 300–700 ms after stimulus presentation. Not a single 100 ms average amplitude turned out to be lateralized reliably. The orientation effect turned out to be reliable in the time range 400–800 ms after stimulus presentation. Each of the four 100 ms average amplitudes was reliably lateralized to the right hemisphere.

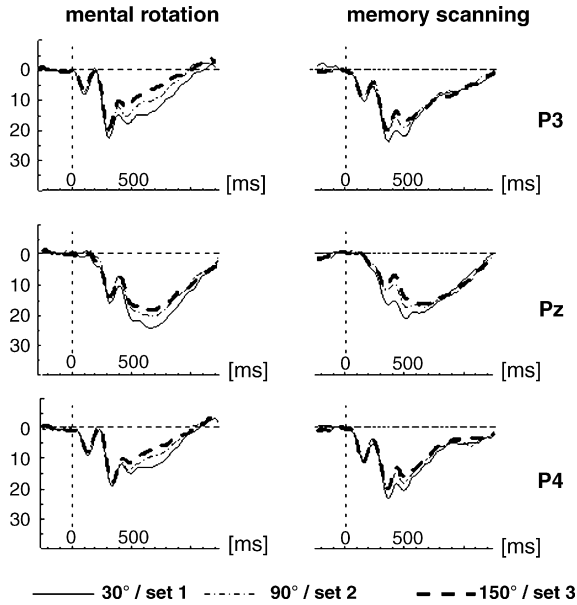


Fig. 1. Grand average ERPs at parietal electrode sites as a function of character orientation in the mental rotation task and as a function of set size in the memory scanning task. Character presentation was at 0 ms. Negativity is up.

(see Fig. 1). The amplitude of the positivity decreased with increasing memory set size ( $F(2, 46) = 16.99, 24.87, \text{ and } 18.33$ , respectively, for P3, Pz, and P4; all;  $p < .01$ ). In order to test for the laterality of the effect, an ANOVA was run with factors set size and laterality (electrodes P3 versus P4). A main effect of set size ( $F(2, 46) = 22.27$ ;  $p < .01$ ) was found whereas the main effect of

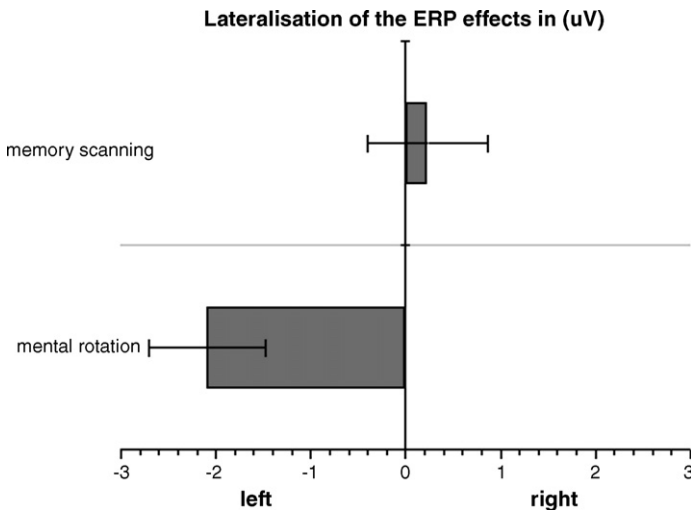


Fig. 2. Hemispheric laterality (left parietal minus right parietal amplitude) of the memory set size ERP effect (difference: set size 3 minus set size 1) and of the mental rotation ERP effect (difference:  $150^\circ$  minus  $30^\circ$ ) at parietal electrode leads. Standard errors of the mean are depicted.

lateralized at all (see Fig. 2).

Finally, an ANOVA was calculated with factors type of task (mental rotation versus memory scanning), laterality (left parietal versus right parietal) and difficulty of the task (three levels of orientation and three levels of set size, respectively). Main effects of type of task ( $F(1, 23) = 7.90$ ) and difficulty ( $F(2, 46) = 47.49$ ; both  $p < .05$ ) as well as a two-way interaction of laterality and difficulty ( $F(2, 46) = 3.73$ ) were found. Most importantly, however, a three-way interaction was obtained ( $F(2, 46) = 3.55$ ; both  $p < .05$ ). As can be seen from Fig. 2, while the effect of increasing orientation during mental rotation was lateralized to the left hemisphere, the effect of increasing set size during memory scanning was not.

### 3. Discussion

The results regarding the reliability and the specificity of the lateralization of ERP effects during mental rotation in children are straightforward indeed. First of all, the amplitude modulation as a function of mental rotation was replicated with children as young as 7 or 8 years. Second, the left lateralization of the amplitude modulation as a function of character orientation was also replicated. The data regarding the specificity of the hemispheric asymmetry are even more intriguing. In our earlier study, we (Jansen-Osmann & Heil, *in press*) observed a substantially greater left compared to right hemisphere amplitude modulation as a function of increasing mental rotation in the younger children that was absent for the older children and the adults. Thus, the effect seemed to be specific for younger children, but it was not clear at all whether the effect was also specific for mental rotation itself. Alternatively, the increasing left hemisphere activation could have been a “simple” consequence of increasing difficulty or of effort needed for any task, might it be mental rotation or any other task. Or, it might have been a consequence of increasing difficulty (effort) of any task that uses letters as stimuli. Both alternative explanations, however, can be discarded on the basis of the memory scanning data. In this task, difficulty is varied as a function of set size, letters are used as stimuli, and an amplitude modulation is observed at parietal leads making it the most critical test for the alternative explanations. Nevertheless, the amplitude modulation as a function of memory set size clearly was not lateralized at all, suggesting that the effect for mental rotation indeed is specific, i.e., it is neither caused by a “simple” increase of difficulty of the task or effort needed, nor by an increase of task difficulty with verbal stimuli.

Taken together, the present data strongly suggest that the left hemisphere activation during mental rotation in elementary school children indeed is both reliable as well as specific. Further studies are definitely needed, however. First of all, the conclusion should be validated by other methods, like lateralized visual field presentation (Cohen & Polich, 1989) or fMRI (Booth et al., 1999). More importantly, it should be investigated whether the effect is general with respect to mental rotation, i.e., is also found when other stimuli than letters are used. The respective studies currently are under way in our laboratory.

Still open, however, is the question of why this pattern of hemispheric asymmetry indeed is observed. The explanation at hand is based on the ideas of Kosslyn (1994) and Corballis (1997). The authors suggested that the left hemisphere is involved in more complex, piecemeal strategies of mental rotation, whereas the right hemisphere is preferentially engaged when the representation as a whole is mentally rotated. More direct tests are needed to evaluate the idea that cognitive development leads to a more holistic rotation process. Some authors argue that a distinction between these two kinds of rotation processes might be possible empirically: whereas

a holistic strategy should result in mental rotation speed being independent of the complexity of the stimulus, an analytic, piecemeal strategy should result in mental rotation speed being a function of stimulus complexity (see, e.g., Bethell-Fox & Shepard, 1988). Substantial empirical work is needed to clarify this aspect under a developmental perspective.

Finally, although completely speculative, one might wonder whether the suggested change from a more analytic to a more holistic processing mode might not only be restricted to mental rotation. A (roughly) similar change at a (roughly) similar age was claimed for, e.g., face processing as well as for face recognition (see Schwarzer & Leder, 2003). It would be fascinating to correlate these developmental changes in processing modes across different tasks, preferentially in a longitudinal approach.

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