Movement Orientation is Related to Mental Rotation in Childhood

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ABSTRACT

The aim of the present study was to find out whether the ability to mentally rotate pictures of animals is associated with motor ability in seven to ten year old children and adults. Results revealed significant correlations between reaction times and percentage correct responses in the mental rotation task and motor orientation errors in the children group only. In contrast, no significant correlations with motor distance errors were found. Given previous literature suggesting that movement orientation is pre-planned to a larger degree than movement distance, the results of the present study suggest that mental rotation is linked to motor control at the level of orientation programming. Moreover, the type of spatial transformation applied in both tasks may play a role, assuming that orientation programming involves the rotation of a vertical movement vector to the orientation of the target with respect to the start position. Finally, the basic ability influencing both mental rotation and orientation programming may be the accurate prediction of consequences of actions.

Keywords: developmental, motor control, mental rotation, human

INTRODUCTION

Though the development of motor control has been studied during the last decades, it remains still unclear why school-aged children show less accurate pointing movements than adults. Looking at functions that develop in parallel with motor control may help to explain these differences. One of these functions is mental rotation, which has been shown to improve with age (Kail 1988; Kail et al. 1980; Kosslyn et al. 1990; Marmor 1975, 1977). In the initiating study on mental rotation by Shepard and Metzler (1971), subjects had to decide whether two three-dimensional block stimuli rotated in space were the same or mirror reversed. The results showed that response time increased linearly with the disparity between the two objects, suggesting that participants solved the task by mentally rotating one of the objects.

Evidence for an association between motor control and mental rotation stems both from functional imaging (Kosslyn et al. 2001; Vingerhoets et al. 2001) and behavioral studies (Funk et al. 2005; Olivier et al. 2004; Wexler et al. 1998; Wiedenbauer and Jansen in press; Wiedenbauer et al. 2007; Wohlschläger 2001; Wohlschläger and Wohlschläger 1998,). In the fMRI study by Kosslyn et al. (2001), subjects first viewed an electric motor rotating an angular object or they rotated the object manually. Then they were asked to imagine the objects rotating as they had just seen the model rotate. Motor cortex activation was found only when subjects imagined manual rotations. In the study by Vingerhoets et al. (2001), subjects had to mentally rotate pictures of hands and pictures of tools. While pairs of hands led to bilateral premotor activations, pairs of tools elicited only left premotor activity. Thus, it appears that if the subject itself causes the imagined rotation or if the afforded action elicited by the presented stimuli is a self-motion, activity in motor areas occurs (see also Tomasino and Rumiati 2004; Zacks et al. 1999).

Behavioral studies firstly showed that mental rotation may be trained by means of manual rotation of equivalent real stimuli both in ten to eleven year old children (Wiedenbauer and Jansen in press) and adults (Wiedenbauer et al. 2007). Further studies revealed interferences and facilitation between mental rotation and parallel hand motor tasks, suggesting that the imagery process involved the simulation of a hand movement. In a study by Funk et al. (2005), children (5-6 years) and adults had to decide if a photograph of a hand in palm or back view and rotated to a certain degree showed a left or a right limb. Participants had to give their responses with their own hands either in a regular, palms-down posture or in an inverted, palms-up posture. For both children and adults, reaction times were the longer, the more awkward it was to bring their own hand into the position shown in the stimulus photograph. Similar results were found in a study by Olivier et al. (2004) in adult subjects.

Wohlschläger and coworkers found that the simultaneous execution of rotational hand movements interfered with mental rotation of three-dimensional cubes, if the direction of movement was incompatible with the direction of mental rotation. They further showed that the mere planning of a rotational hand movement was sufficient to cause this interference (Wohlschläger and Wohlschläger 1998, Wohlschläger 2001). Wexler et al. (1998) showed that during mental rotation of abstract shapes, an accompanying unseen hand movement in a direction compatible with the mental rotation produced faster performance than an incompatible movement (see also Sirigu and Duhamel 2001).

Surprisingly, there are also studies in which an association between mental rotation and motor control was found despite the fact that the subject was not imagining a self-motion or was not in itself the cause of an imagined object movement. However, such studies are rare. In a study by Sirigu and Duhamel (2001), subjects were asked to imagine the experimenter rotating his own hand. Even with this “third-person visual imagery” an influence of the subject’s own hand posture on mental rotation was found. Moreover, an fMRI study by Kucian et al. (2006) showed that mere mental rotation of 2D images of animals led to an activation of motor areas in children and adults.

The question remains if covert motor activation may automatically occur in any imagery task in which some kind of spatial transformation has to be applied to the content of the mental representation (Funk et al. 2005). Secondly, one may ask if correlations between mental rotation and motor tasks are also found when the type of movement is dissimilar to the type of spatial transformation applied in the imagery task. Given that many of our everyday movements are translational movements to a target, we decided to investigate whether pointing accuracy in a translational movement task is associated with a mental rotation of objects in 7 to 10 year old children and adults. In contrast to previous interference studies, the two tasks were performed subsequently, with an additional task in between. This was done to reduce “motor connotations” in the mental rotation task.

METHODS

Subjects

Nineteen children aged 7 to 10 years participated in the study. Based on the observation that crucial steps in motor development are found at the age of 7-8 and 9-10 years (Bard et al. 1990; Hay et al. 1991), two children groups were differentiated: seven to eight years (mean 7.4 ± 0.5 years, 5 boys, 4 girls), and nine to ten years (mean 9.4 ± 0.5 years, 5 boys, 5 girls). All children were right-handed. An adults' control group (n = 9) had an age range of 20 to 28 years (mean 24.4 ± 3.6 years) and consisted of 6 women and 3 men, all right-handed. None of the subjects had a history of neurological illness or developmental problems. Written informed consent was obtained from all participants or parents, who were recompensed for their travel expenses. The local committee of research ethics approved the study.

Experimental setup

Motor task

The motor task was performed first and took about 10 minutes. Subjects sat comfortably at a table in front of a stack of 30 sheets of white paper (29.7 x 42.0 cm). On each of the sheets, two black dots (diameter 0.6 cm) were printed. One dot was located in the lower middle of the sheet, representing the start position. The other dot was located in one out of 15 possible target positions. The latter were defined by three different target distances (5.6, 11.2, and 16.8 cm) and five different target orientations (from left to right: 54°, 72°, 90°, 108°, 126°).

The subject's task was to look at each sheet for about 3 seconds, place a pencil that he or she was holding in the hand on the start position, close the eyes and draw a line to the target position. Then, without opening the eyes, the sheet was taken away and the subject was asked to open his or her eyes again to see the next sheet. There were two blocks of trials in each of which the target was presented at all 15 target positions in the same random order.

The following variables were determined on the basis of the coordinates of the actual end positions (see Figure 1). <u>Distance error.</u> The distance between the start and end position (movement distance, Dm) was calculated according to the Pythagorean theorem as $\mathrm{sqrt}[(Xm-Xs)^2+(Ym-Ys)^2]$, with Xs and Ys being the x- and y-values of the start position and Xm and Ym the x- and y-values of the end position. Target distance (i.e., 5.6 cm, 11.2 cm, and 16.8 cm) was then subtracted from movement distance to get a measure of target overshoot (positive error) and undershoot (negative error).

Orientation error [°]. First the sinus of the angle built by the movement's end position with respect to the start position (α_m) was calulated by dividing the difference between the y-values of the start (Ys) and end position (Ym) by the movement distance: sin α_m = opposite leg/hypotenuse = (Ym-Ys)/movement distance. Then, the value of α_m was determined as arcus sinus α_m. Target orientation (i.e., 54°, 72°, 90°, 108°, 126°) was subsequently subtracted from actual movement orientation so that negative values resulted when actual movement orientation was smaller than (or leftwards of) the target orientation. The constant (i.e. signed) and absolute distance and orientation errors were averaged across the two trials of each target and then across the 15 means of each target.

Please insert Figure 1 about here

Mental rotation task

The mental rotation task was applied after the motor task and took about 10 minutes. It was implemented on an IBM notebook by means of E-Prime Software (Psychology Software Tools, Inc., Pittsburgh, USA). Two stimuli were presented on a 15inch monitor and the subject was asked to indicate by a button press if the two stimuli were alike or not. The buttons were two keys on a standard keyboard, 0 for „alike“ and 1 for „not alike“. Subjects were told that both accuracy and reaction time were equally important. Coloured paintings of 11 different types of animals were presented on white background. The pictures were taken from the coloured set of the Snodgrass and Vanderwart pictures (Rossion and Pourtois 2004; Snodgrass and Vanderwart 1980). In one condition, the animals stood on their feet and looked either towards each other or towards the side (line of sight not alike, not rotated). In another condition, both animals stood on their feet and both looked either to the left or to the right (line of sight alike, not rotated). There were two parallel rotated conditions, in which the right animal was turned upside down (line of sight not alike, rotated; line of sight alike, rotated). Thus, there were eight trials per animal type and 88 trials in total.

After each trial, subjects got feedback about the correctness of their response. There were five types of yellow feedback stimuli. If the reaction was correct, a “loughing star” (children) or a loughing smiley (adults) was shown. If the reaction was wrong, an exclamation mark (children) or a sad smiley (adults) appeared. If no reaction occured, a question mark was shown. There was a training block of 12 trials in the children, using stimuli different from that in the actual experiment.

Following a verbal and written instruction, the subjects were asked to get ready for the task (2000ms) and to look at a fixation cross (2000ms), which was subsequently shown for 1000ms. The stimulus was presented for a maximum of 5000ms, followed by the respective feedback stimulus (1500ms). Finally, the subject was shown the percentage (adults) or absolute number (children) of correct answers up to the present trial and asked to press a button to go on with the next trial.

RESULTS

Developmental achievements in the motor and visuospatial tasks

In the motor task, we calculated a multivariate analysis of variance with age as independent variable and orientation and distance errors as dependent variables. There was a trend for distance and orientation errors to increase with age. However, the MANOVA showed no significant age effects (all P's$\geq$0.152). The means of the error measures in the three age groups are shown in Table 1.

Percentage correct responses and reaction times in correct trials of the mental rotation task were analysed by means of a multivariate analysis of variance with the factors rotation (yes, no) and age (7-8 years, 9-10 years, adults) (see Table 2). Reaction times decreased with age ($P<0.0001$). Post-hoc tests showed that adults significantly differed both from older ($P<0.0001$) and younger children ($P<0.0001$), which did not differ from each other ($P=1.000$). Moreover, rotated stimuli yielded slower responses than non-rotated stimuli ($P<0.0001$). Finally, there was a significant main effect of rotation ($P=0.009$) and age ($P=0.013$) on percentage correct responses. Adults significantly differed from the younger ($P=0.012$), but not the older children ($P=0.826$), which did not differ from each other ($P=0.152$). The interaction effects were not significant (P's>0.165).

Mental rotation ability correlates with orientation errors in children

For the correlation analyses the two children groups were collapsed and compared with the adults. This was done as there were no significant differences between the two children groups both in the motor and the mental rotation task. In the adults, there were no significant correlations between motor errors and reaction times or percentage correct responses in the mental rotation task (P's≥0.161). In the children, absolute orientation error increased significantly with reaction times in the mental rotation task (r=0.517, P=0.024; all other correlations P≥0.962; see Figure 2). Moreover, percentage correct responses was the larger, the more negative (i.e. to the left of the target) constant orientation error (r=-0.497, P=0.030; all other correlations P≥0.141). Thereby, apart from two subjects with a mean constant orientation error smaller than -4°, all other errors ranged between –3 and +2°. The tendency to miss the target on the right was likely associated with the strategy to use less inward rotation of the shoulder in addition to the required extension of the elbow, which is likely a reflection of the fact that the planning of multi-joint movements is more complex than the planning of single-joint movements (Seidler et al. 2002).

Finally, differences between the younger and older children may not explain the correlations found in the collaped children group. Additional correlation analyses with age as control variable (partial correlations) revealed similar results as in the main analysis.

Please insert Figure 2 about here

DISCUSSION

The main result of the present study was that the ability to mentally rotate pictures of animals was associated with the accuracy of translational target movements in the children group, suggesting that – at least in childhood – the two tasks share some crucial process.

In contrast to previous studies, the reference to self-motion or self-induced object motions was reduced in the present study. Firstly, pictures of animals were used instead of pictures of hands or tools. Secondly, another visuospatial task (the results of which are not presented here) was performed in between the motor and the mental rotation task. Thus it seems implausible that children were thinking of the movement task when doing the mental rotation task. Thirdly, no instruction was given to the children that they should imagine to rotate the pictures "by themselves". Consequently, at least with children, our results are in accordance with the idea that covert motor activation may automatically occur in any imagery task in which some kind of spatial transformation must be applied to the content of the mental representation. However, the question remains why no significant correlations were found between mental object rotation and motor performance in adults. This may be the results of the small sample size. Besides, ceiling effects may play a role, since both tasks, motor and imagery, turned out to be very easy for the adults.

Significant correlations were found for orientation errors only, suggesting that movement orientation and distance are independent components in motor control. Evidence in favor of the latter idea has been found before both for children (Bard et al. 1990; Barral and Debu 2002; Hay et al. 1991) and adults (Rosenbaum 1980; Soechting and Flanders 1989; Chieffi and Allport 1997). More importantly, it has been suggested that the orientation component is programmed to a larger degree than the distance component, which is more strongly dependent on visual feedback (Bédard and Proteau 2004; Messier and Kalaska 1999; Soechting and Flanders 1989). Taken together our results may support the assumption that mental rotation and motor control are linked at the level of motor programming (Wohlschläger and Wohlschläger 1998, Wohlschläger 2001).

Our results further suggest that an association between motor control and mental rotation is not limited to certain hand positions or rotational hand movements, but may also be applied to translational target movements. Thus at first glance the type of spatial transformation is not a crucial factor. However, even the control of translational movements may, to some extent, require rotational tranformations. This is to say, the planning of movement direction may require the rotation of a vertical movement vector to the orientation of the target with respect to the start position. This may also explain the dissociation of correlations regarding orientation and distance errors.

Finally, one may ask what basic ability underlies imagining a spatial transformation like rotation. It appears that subjects are essentially supposed to predict or anticipate the consequences of a certain action on the contents of the mental representation. This interpretation holds both for orientation programming as described above and mental rotation. Moreover, it is important to note that prediction is part of the motor control system in the form of so-called internal forward models anticipating the sensory consequences of certain motor commands sent to the muscles (for a discussion of the role of forward models in motor control see Frith et al. 2000). Considering the developmental perspective, it was found that although already 6 year old children may use internal forward models in motor control (Hay et al. 1994), their function is not yet mature (Contreras-Vidal 2006).

CONCLUSION

The results of the present study suggest that mental rotation is linked to motor control at the level of orientation programming. Moreover, the type of spatial transformation applied in both tasks may play a role, assuming that orientation programming involves a rotational transformation. Finally, the basic ability influencing both mental rotation and orientation programming may be the accurate prediction of consequences of actions.

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FIGURE LEGENDS

Figure 1: Computation of error measures. Distance error was based on the difference between movement and target distance, with movement distance = sqrt[(Xm-Xs)²+(Ym-Ys)²]. Orientation error was based on the difference between movement and target orientation, the former calculated as sin α_m = (Ym-Ys)/movement distance.

Figure 2: Results of the correlation analysis. In the children, reaction times in the mental rotation task significantly correlated with absolute orientation error (r=0.517, P=0.024. Moreover, percentage correct responses in the mental rotation task significantly correlated with constant orientation error (r=-0.497, P=0.030).

Table 1: Mean distance [mm] and orientation errors [°] and standard deviations for the different age groups, target distances and target orientations

	Distance Error [mm]		Orientation Error [°]	
	Constant	**Absolute**	**Constant**	**Absolute**
Age group	P=0.152	P=0.197	P=0.432	P=0.306
7-8 years	-13.30±11.98	17.56±8.25	-1.43±3.02	3.92±1.03
9-10 years	-18.87±14.19	21.99±10.04	-0.11±1.65	3.20±0.80
Adults	-7.04±13.03	15.12±6.37	-0.60±1.77	3.26±1.99

Table 2: Mean reaction times [ms] and percentage correct responses and standard deviations for the different experimental factors in the mental rotation task

	Reaction Time [ms]	**Correct Responses [%]**
Age group	P<0.0001	P=0.013
7-8 years	1741.18±438.21	87.63±15.75
9-10 years	1756.79±506.93	93.98±7.60
Adults	1131.16±271.57	97.47±3.89
Rotation	P<0.0001	P=0.009
No	1264.83±350.17	96.59±4.89
Yes	1836.52±478.62	89.53±13.78

Figure 1:

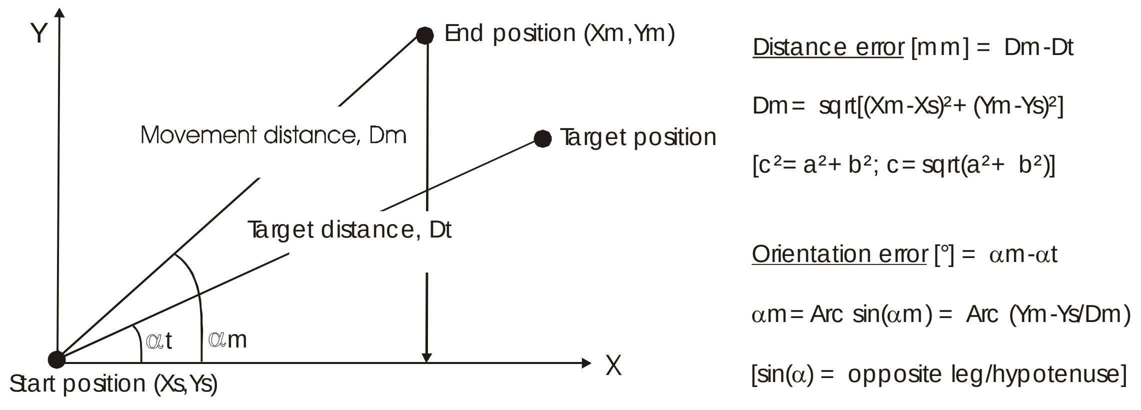

Figure 2: