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REPORT

Motor processes in children's imagery: the case of mental rotation of hands

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Abstract

In a mental rotation task, children 5 and 6 years of age and adults had to decide as quickly as possible if a photograph of a hand showed a left or a right limb. The visually presented hands were left and right hands in palm or in back view, presented in four different angles of rotation. 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, variation of the posture of their own hand had a significant effect. Reaction times were longer the more awkward it was to bring their own hand into the position shown in the stimulus photograph. These results, together with other converging evidence, strongly suggest that young children's kinetic imagery is guided by motor processes, even more so than adults'.

Introduction

Several studies have shown that children as young as 5 years of age have kinetic imagery, that is, imagery representing movement (e.g. Marmor, 1975, 1977; Kosslyn, Margolis, Barrett, Goldknopf & Daly, 1990). In earlier work, Piaget and Inhelder (1971) had claimed that this ability develops considerably later, only after children have entered the stage of concrete operations. Under 7 years of age, according to Piaget and Inhelder's notion, children can have only static images. The question of what the properties of children's imagery are and when it develops has far-reaching implications for issues of cognitive development in general. If kinetic imagery actually plays a central role in children's thinking, then its properties will place major constraints on various cognitive processes that have been the focus of developmental research with young children. Outstanding examples, to name just two, are perspective taking abilities (e.g. Perner, 1991) and reasoning about the consequences of movement and object transformations in children's intuitive physics (e.g. Wilkening & Huber, 2002).

Young children's kinetic imagery abilities have been most clearly shown in variants of the mental rotation paradigm originally designed by Shepard and Metzler (1971) for studies with adults. In these experiments, pairs of relatively complex geometrical objects that were either identical or mirror images of each other were shown, and the task of the participants was to decide as fast as possible if the two objects were the same or not. What made the task difficult was that the two objects differed in their orientation in space, with varying degrees of angular disparity. The response times increased linearly with the size of the angle, suggesting that the participants had mentally rotated one of the two objects, until it was congruent with the other one. This result has since been replicated in many studies with adults (e.g. Kosslyn, 1994; Parsons, Fox, Downs, Glass, Hirsch, Martin, Jerabek & Lancaster, 1995; Shepard & Cooper, 1982) and with children of different ages (e.g. Kail, Pellegrino & Carter, 1980; Levine, Huttenlocher, Taylor & Langrock, 1999; Marmor, 1975, 1977). It should be noted that in most of the developmental experiments, the three-dimensional forms of the Shepard and Metzler paradigm were replaced by two-dimensional stimuli. In the seminal developmental study by Marmor (1975), for instance, children were shown drawings of panda bears in different orientations in the picture plane, and the task was to decide whether the two bears in each pair were the same or different.

In recent years, the research focus has shifted from simply demonstrating the existence of kinetic imagery to

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a deeper understanding of the nature of the phenomena. It appears that a host of processes is involved, and that mental rotation is less 'mental' and more reliant on representations of one's own moving body than was previously conceived. In particular, mental rotation seems to be guided by motor processes, with the motor system being the engine driving the cognitive operations, rather than just the output system as it is usually seen (Wexler, Kosslyn & Berthoz, 1998). The most striking evidence for this view comes from experiments in which pictures of rotated human body parts such as hands had to be identified. Using neuroimaging techniques, Kosslyn, Di Girolamo, Thompson and Alpert (1998) showed that mental rotation of pictures of hands activated the primary motor cortex and associated higher-order motor areas, which was not the case in mental rotations of the geometric objects used by Shepard and Metzler.

Based on data like these, the authors proposed the existence of two distinct mechanisms in mental rotation: (a) an internal strategy, in which the person anticipates what she would see if she were to produce the rotation herself by a physical manipulation, and (b) an external strategy, in which the person attempts to visualize the consequences of a movement produced by some external force. In this view, only the internal mechanism recruits processes that prepare motor movements, while the external mechanism does not. The findings of Kosslyn *et al.* were largely corroborated, and partly elaborated, in several follow-up neuroscience studies (e.g. Kosslyn, Thompson, Wraga & Alpert, 2001; Thayer, Johnson, Corballis & Hamm, 2001; Vingerhoets, de Lange, Vandemaele, Deblaere & Achten, 2002). Ganis, Keenan, Kosslyn and Pascual-Leone (2000) took the line of reasoning one step further, by showing that disruption of primary motor cortex functioning by transcranial magnetic stimulation (TMS) slowed down the speed of mental rotation of pictures of hands, a result strongly suggesting that motor processes may even play a causal role.

The conclusions drawn from recent neuroimaging data are in accordance with behavioural data that had been obtained in earlier work (e.g. Sekiyama, 1982). Most notable is a study by Parsons (1994), in which adult participants had to decide whether a picture showed a left or a right hand, the hands being portrayed in palm or back view in different orientation in space. Reaction times (RTs) depended strongly on the awkwardness of the movement the participants would have to perform physically to rotate their own hand into the depicted position. By varying the position of the participants' hands during the experiment, Parsons could show that the spatial origin from which the simulated action started was as decisive a factor as was the 'canonical' view of the pictured hand.

The idea of a canonical orientation had been put forward by Cooper and Shepard (1975) in their seminal experiment on laterality decisions of visually presented hands ('a left or a right hand?'). Their participants showed a clear reaction time (RT) advantage for stimulus hands with the fingers pointing upward compared to downward. Cooper and Shepard discussed two possible reasons for this effect. First, they emphasized the fact that people see their own hands in a position with fingers down less often, and that the more canonical fingers-up view would therefore facilitate RTs. Second, referring to some of their subjects' introspective reports, they already considered postural-kinaesthetic constraints and referred to the 'physical awkwardness of positioning one's own (right or left) hand in that inverted orientation' (p. 54). The notion of canonical visual representations favouring some stimulus hands over others was also discussed with respect to an advantage, in hand laterality decision tasks, for back vs. palm views of hands. It was argued (e.g. Ashton, McFarland, Walsh & White, 1978) that this advantage arises from a more frequent visual exposure to one's own backs of hands than palms. An alternative explanation, however, would be that participants in experiments like those mentioned here regularly hold their hands in a palms-down posture while performing the RT task. RTs to backs of hands might thus be faster because this stimulus does not require any kinaesthetic imagery of a hand rotation around the wrist.

Surprisingly, there are virtually no developmental data contributing to the debate on the relative importance of visual vs. kinaesthetic canonical representations for successful performance in tasks requiring the mental rotation of body parts. Such data may shed additional light on some important issues in the field. For instance, if the effect of past visual experience (i.e. the canonical *view* effect) were a primary factor, one should not expect a stronger effect in young children, because it is implausible to assume that in their visual experience the advantage for finger-up or back hand views would be greater compared to adults. In contrast, if motor-kinaesthetic factors were more decisive, one would predict stronger effects in young children because, according to the prevalent view, sensorimotor and visual processes are more tightly coupled than at older ages (Bertenthal & Clifton, 1998; Piaget, 1954; Rosenbaum, Carlson & Gilmore, 2001). In any case, it seems desirable to back up the current discussion with developmental data from children at the age that has been of interest in other research on mental rotation and to extend the hand rotation task to children. The present experiment is a first attempt in this direction.

To further investigate the coupling of sensorimotor and visual processes, we introduced a variation of the hand posture. During the experiment, children and adults held their own hands either with their palms down (i.e. backs up) or palms up (i.e. backs down). In accordance with the existing literature, we predicted a clear advantage for judging back views over judging palm views when the subject's own hand is in the regular palm-down posture. Specifically, for the novel variation introduced in this experiment, we expected a reduction of the back-view advantage when the subject's own hand had the opposite posture during responding, that is, palm up. Of particular interest was the question whether this effect, if it should occur at all, would be smaller or larger for children than for adults. If it turned out to be larger, this could be taken as an indication of the fact that for children, in particular, the posture of their own hand plays an important role when judging visually presented hands and, thus, would provide strong support for the view that their kinetic images are tightly coupled to and even may be guided by motor processes.

Preliminary study

In a preliminary study, we wanted to make sure that the children who would take part in the main experiment were able to (a) make left–right discriminations and (b) perform mental rotations of pictures of objects other than parts of the human body.

Method

Participants

Participants were 22 children (11 boys and 11 girls) from two kindergarten classes in Zurich, Switzerland. Ages ranged from 5 years 5 months to 7 years 2 months; the mean age was 6.6 years (SD = 0.6 years).

Materials

Stimuli were 24 ($3 \times 4 \times 2$) drawings of cars, including three different types of cars, each in four angles of rotation, 0°, 90°, 180° or 270° along the vertical axis, and in two driving directions, facing to the left or to the right in the unrotated position of 0° (see Figure 1 for three sample stimuli). The stimuli were presented on a portable Macintosh computer in the centre of the monitor. They extended a visual angle of maximally 12° both horizontally and vertically. Responses were given via two buttons fixed on a wooden keyboard which lay on the table in front of the Laptop, the two buttons being 32 cm apart.

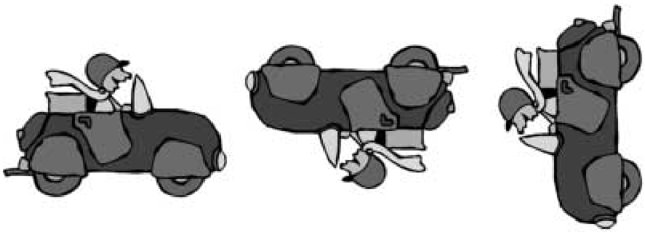

Figure 1 *Three sample stimuli out of the set of 24 stimuli used in the preliminary study. Shown is one of the three types of cars used, in a 0°, 180° and 270° view, from left to right.*

Procedure

The children's task was to find out whether the presented car would drive to the left or to the right. Obviously, cars that were not in a horizontal position had to be (mentally) rotated for that purpose. Children were told that if they concluded that the car's driving direction was to the right, they should press with their right hand the right button, and if they concluded that the driving direction was to the left, press with their left hand the left button. Each child judged the 24 stimuli in three different random orders. Children were encouraged to give their decisions as fast and as correctly as possible. Stimulus exposure was terminated by the child's pressing of the button (left or right).

Results and discussion

The chance level of correct responses in the present task was 36, half of the total of 72 possible. Individual performance was significantly above chance level if the number of correct responses was 45 or more, $p < .05$. This was the case for 20 out of the 22 children. The two children who failed to reach the criterion, one boy and one girl, gave 43 and 41 correct responses, respectively. Their data were discarded from further analyses. For the remaining 20 children, the percentage of correct responses was 99%, 94%, 65% and 94%, for the rotation angles of 0°, 90°, 180° and 270°, respectively.

A three-way repeated measures ANOVA of the RTs of correct responses (with gender as between-subject factor and rotation angle and left–right orientation as within-subject factors) yielded, as expected, a significant main effect for rotation angle, $F(3, 54) = 44.06$, $p < .01$, reflecting a significant increase in RTs with the increase of the rotation angle of the stimulus to be judged from the standard orientation of 0° or 360°. RTs were significantly different from one another for all pairs of rotation angles, $ts(19) > 4.77$, $p < .01$, except for those of 90° and 270°, $t(19) < 1$. No other main effects or interactions were significant.

Figure 2 *Four sample stimuli out of the set of 16 different stimuli used in the main experiment, with palm or back views of a left or a right hand in four degrees of rotation, 0°, 90°, 180° and 270°.*

The results of this preliminary study clearly show that children of kindergarten age can use mental rotation in making left–right decisions about two-dimensional objects. In view of evidence from previous studies indicating that mental rotation abilities undergo a strong development around the age of 5 to 6 years, it is interesting to note that those two children who failed to reach the criterion were the two youngest participants in this study, both 5-year-olds. All other children were found to have the basic qualifications for participation in the main experiment.

Main experiment

Methods

Participants

Those 20 children who had performed above chance level in the preliminary study participated in the main experiment. Of those, five girls and three boys were excluded from main data analyses because their performance did not exceed the chance level in this experiment (see below). Data will thus be reported for the remaining 12 children, five girls with a mean age of 6.7 years (SD = 0.5 years), and seven boys with a mean age of 6.6 years (SD = 0.6 years). All of these children showed a clear right-hand preference according to performance-based criteria from the NEPSY test battery (Korkman, Kirk & Kemp, 1998).

In addition to the children, 24 adults, 12 male and 12 female, participated in this main experiment. Ages ranged from 20 to 40 years (M = 31.74, SD = 8.32). Most adult participants were students or had already received an academic degree, all 24 were right-handed, assessed by the inventory of Chapman and Chapman (1987).

Materials

Stimuli were 16 ($2 \times 2 \times 4$) photographs of human hands, left and right hands, each with palm or back view, that is, with a rotation along the longitudinal axis of the arm, each in four different rotation angles along the perpendicular axis of the arm, 0°, 90°, 180° or 270° (see Fig. 2). The photographs were presented on a portable Macintosh computer in the centre of the monitor. Maximal horizontal and vertical extension was 12° of visual angle, as for the cars in the preliminary study. Responses for left–right decisions were given via the same keyboard used in the preliminary experiment. For the inverted response condition introduced here (palms up), the keyboard could be turned upside down.

Procedure

Participants had to decide as fast and correctly as possible whether the presented hand was a right or a left one. Left–right decisions had to be given by pressing a left or a right response key on the ipsilateral side of the keyboard. Stimulus exposure was terminated by the participant's pressing of the response key or by the exposure time limit of 7000 ms for the children and 3000 ms for the adults. In each response condition, the 16 stimuli were presented in three different random orders for the children and in four different random orders for the adults. In one response condition, the key had to be pressed in a regular hand posture, that is, palms down. In the other response condition, the key had to be pressed upward in an inverted posture, that is, palms up, under the same keyboard. In both conditions, participants' hands and forearms were covered by a cloth to prevent the view of their own limbs (see Fig. 3). Presentation order of the two response conditions was counterbalanced in both age groups.

Results

Children

For children, chance level of correct responses was 48, half of the total of 96 stimulus presentations. Individual performance was significantly above chance level when

Figure 3 *A child performing the task with a regular, palms-down posture (left side) and with an inverted, palms-up response posture (right side). Note: The cloth that covered participants' hands in both response conditions is not shown here; their hands were totally invisible to them while responding.*

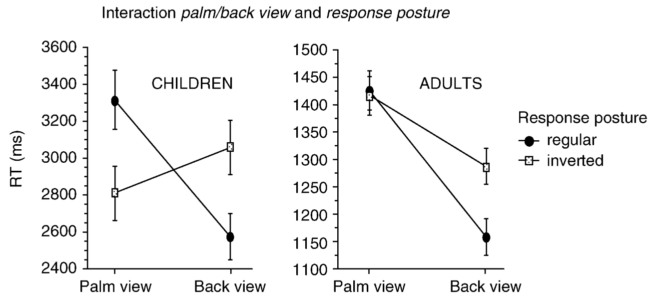

Figure 4 *Mean RTs of children (left panel) and adults (right panel) for visually presented hands in palm or back view in the two response conditions: regular and inverted posture of own hands.*

the number of correct responses was 58 or more, $p < .05$. This was the case for 12 out of the 20 children. The data of those eight children who did not reach the criterion were discarded from further analyses.

A five-way repeated measures ANOVA of the RTs of the 12 children's correct responses,[1] with gender as a between-subjects factor and stimulus laterality, palm-back view, rotation angle, and response posture as within-subjects factors, revealed a significant main effect of rotation angle, $F(3, 30) = 9.50$, $p < .01$, in line with the pattern to be expected for mental rotation. With increasing distance of the rotation angle from the 0° or the 360° orientation, respectively, mean RTs increased. They were significantly different from one another for all pairs of angles, $ts(11) > 2.42$, $p < .05$, except for the 90°–270° pair, both rotations with fingers in horizontal orientation, $t(11) < 1$.

Significant interactions were found between (a) stimulus laterality and palm-back view, $F(1, 10) = 8.94$, $p < .05$, (b) palm-back view and rotation angle, $F(3, 30) = 5.08$, $p < .01$, and (c) stimulus laterality and rotation angle, $F(3, 30) = 6.16$, $p < .01$. These interactions reflected (a) faster responses for back compared to palm views for right hands, $t(11) = 3.38$, $p < .01$, but not for left hands, $t(11) < 1$, (b) faster responses for back views at 90°, for palm views at 180°, and no RT advantage of back or palm view at 0° and 270°, and (c) faster responses for left hands at 90°, $t(11) = 2.96$, $p < .05$, but for right hands at 270°, $t(11) = 2.31$, $p < .05$, whereas there was no RT advantage of either hand at 0° and 180°.

Crucially, there was also a significant interaction of palm-back view and response posture, $F(1, 10) = 17.58$, $p < .01$. While back views of pictures of hands were recognized significantly faster than palm views when the own hand was in the regular, backs-up response posture, $t(11) = 4.95$, $p < .01$, this was not the case for the inverted response posture. In fact, when children responded with their palms up, there was a numerically, even if statistically not significant RT advantage for recognizing pictures of palms (see Fig. 4, left panel).

Adults

All adults performed above chance level as to their left–right decisions on the individual level. The analogous ANOVA of their RTs for correct responses yielded three significant main effects: pictures of backs were recognized faster than pictures of palms, $F(1, 22) = 17.62$, $p < .01$, pictures of right hands were recognized faster than pictures of left hands, $F(1, 22) = 36.03$, $p < .01$, and RTs increased with an increasing distance in rotation angle from the unrotated, fingers-up orientation of the hand, $F(3, 66) = 45.53$, $p < .01$, according to the pattern to be expected for mental rotation: mean RTs were significantly different from one another for all pairs of rotation angles, $ts(23) > 3.55$, $p < .01$, except for the 90°–270° pair, $t(23) < 1$.

In addition to the three significant main effects, three significant two-way interactions were found: First, there was a significant interaction of palm-back view and rotation angle, $F(3, 66) = 6.56$, $p < .01$, reflecting the fact that backs were recognized significantly faster than palms at rotation angles of 0°, 90° and 270°, $ts(23) > 3.79$, $p < .01$ but not at 180°, $t < 1$. Second, there was a significant interaction of stimulus laterality and rotation angle, $F(3, 66) = 15.03$, $p < .01$, due to faster RTs for right hands at rotation angles of 0°, 180° and 270°, $ts(23) > 2.90$, $p < .01$, and for left hands at 90°, $t(23) = 2.99$, $p < .01$.

[1] RTs of correct responses correlated negatively, $r = -.22$, $p < .01$, with accuracy, measured via number of correct decisions. That is, correctness of decisions was associated with faster rather than slower responses. Thus, the RTs presented here do not reflect a speed–accuracy tradeoff – a finding that further strengthens the analyses based on RTs.

Third and most importantly, there was a significant interaction of palm-back view and response posture, $F(1, 22) = 7.50$, $p < .01$. Although the adults responded to back views significantly faster than to palm views in both posture conditions of their own hand, $t(23) = 5.30$, $p < .01$ for the regular, backs-up condition and $t(23) = 2.30$, $p < .05$ for the inverted, palms-up condition, the postural manipulation significantly reduced the back view advantage, $t(23) = 2.30$, $p < .01$. In other words, when adults could hold their own hands in palms-up posture, they recognized palm-view pictures of rotated hands virtually as fast as in the regular backs-up posture, whereas for the back-view pictures they were clearly slower when they held their own hands in the inverted palms-up posture (see Fig. 4, right panel). This interaction indicates that the time taken for mental rotation of visually presented hands is not independent of the momentary posture of the person's own hand.

General discussion

The present results replicate well-known findings from previous studies (e.g. Marmor, 1975; Kosslyn *et al.*, 1990) showing that children by the age of 6 years have the ability to mentally rotate visually presented objects, which implies that their imagery is not just static, but also kinetic. This was clearly demonstrated in our preliminary study, in which the objects to be mentally rotated were pictures of cars, and also in the main experiment, in which the objects to be mentally rotated were pictures of hands. In addition to what is already known from previous studies in the field, the present data show that children at kindergarten age can not only mentally rotate when they have to recognize the sameness, that is, the congruence of visually presented objects but also when they have to make left–right decisions about them.

Because, in the main experiment, unlike in the previous developmental studies on kinetic imagery, we used pictures of parts of the human body as stimuli to be rotated, we could investigate whether and how children's mental rotation and thus their kinetic imagery is guided by motor processes. For this purpose, we introduced a novel variation of the task: During the experiment, the children (as well as the adults) held their own hands either in the regular, palms-down or in the inverted, palms-up posture. An interesting question, then, was if RTs for the visually presented hands, left and right ones in palm or back view, were particularly long when it would be difficult and physically awkward to bring the hand of the own body into that position. For example, for most people it is physically much more awkward to bring their right hand in palm view to a 90° position, fingers pointing to the right, than to a 270° position, fingers pointing to the left.

In the present data there are many indications for contributions of motor processes in children's kinetic imagery. Most compelling is the interaction of palm-back view of the visually presented hands and the posture of the own hand, which turned out to be significant for children and for adults. For children, the usual RT advantage for back views of hands was completely eliminated when they had their own hands in palms-up posture. In this condition, they correctly identified the pictures of left or right hands even faster when they were presented in palm view. For adults, the back-view advantage in RTs still existed in the inverted, palms-up posture, although highly reduced. Thus, it may be concluded that the effect of the posture variation was even more remarkable for the children than for the adults. It is hard to find an explanation of this effect that would not in some way refer to children's implicit attempts to bring their own left or right hand – starting from its momentary posture – in the position that was presented in the visual stimulus. Recall that children could not see their own hands during all experimental trials.

There are several other pieces of supporting evidence, pointing to the contribution of motor processes: for instance, pictures of left hands were recognized faster in the 90° position, fingers pointing to the right, than in the 270° position, fingers pointing to the left, while the reverse was true for pictures of the right hand. Furthermore, pictures of hands that were in the same position as the child's own hand, that is, fingers up, were generally recognized faster than those of the same hands rotated by 180°, that is, fingers down. Although these two effects can, at least in principle, be explained via visual experience, referring to the fact that people see their own hands more often in the 'canonical' fingers-up position (Cooper & Shepard, 1975), an explanation taking motor processes into account appears to be the more plausible one, particularly if these data are seen in combination with the unequivocal results on posture variation just discussed.

Besides contributing to the main question of the present experiment, the posture variation data obtained here can also be seen as relevant to the vast literature on mental rotation in adults. These data strongly suggest that the usual RT advantage for hands in back view is at least in part due to the postural bias present in conventional hand laterality tasks, and they emphasize the role of proprioception in the visual recognition of hands. Furthermore, the same data corroborate the view that adults' kinetic images are guided by motor processes, as discussed in the recent literature in cognitive psychology and neuroscience (e.g. Wexler *et al.*, 1998; Vingerhoets *et al.*, 2002).

In view of the present data, this point can be made even more strongly for children. For them, the effects indicative of motor processes were generally even higher than those found for adults. This is in line with the view that perceptual and sensorimotor processes are more tightly linked in young children than in adults, put forward and popularized by Piaget (1954). Also, our data are in accordance with a more modern version of this general view, the hypothesis that all intellectual skills – imagery included – are 'performatory', that is that all skills are grounded in and supported by motor activity, even at high levels (Rosenbaum *et al.*, 2001).

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