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Does the Motor System Facilitate Spatial Cognition?

Effects of Motor Action and Perception on Spatial Imagery in Human Development

Markus Krüger and Horst Krist
Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany

Author Note

Markus Krüger and Horst Krist, Institut für Psychologie, Ernst-Moritz-Arndt-Universität Greifswald.

We wish to thank Sötje Peter, Alexandra Armbrust, and Juliane Schmidt for assistance in data collection.

Correspondence should be sent to Markus Krüger, EMAU Greifswald, Institut für Psychologie, Entwicklungspsychologie und Pädagogische Psychologie, Franz-Mehring-Str. 47, 17487 Greifswald, Germany.
Phone: ++49-3834-863780
Fax: ++49-3834-863763
E-mail: markuskr@uni-greifswald.de

Abstract

Recent studies have established a link between the motor system and imagery in children (e.g., Frick, Daum, Walser, & Mast, 2009; Krüger & Krist, 2009a; Schwarzer, Freitag, & Buckel, 2010). A motor effect on imagery is demonstrated by the influence of stimuli related movement constraints (i.e., constraints defined by the musculosceletal system) on mental rotation (Shepard & Metzler, 1971), or by interference effects of the participants' own body movements or body postures. This link is usually seen as qualitatively different or stronger in children as opposed to adults. In the present research, we put this interpretation to further scrutiny using a new paradigm: In a motor condition we asked our participants (kindergartners and third-graders) to manually rotate a circular board with a covered picture on it. This condition was compared to a perceptual condition where the board was rotated by an experimenter. Additionally, in a pure imagery condition, children were instructed to merely imagine the rotation of the board. Children's task was to mark the presumed end position of a salient detail of the respective picture. Contrary to what embodiment theories would predict, there was no difference in participants' performance between the active rotation and the passive rotation condition. However, children's performance was clearly the worst in the pure imagery condition. This suggests that young children depend heavily on external support when imagining rotations or other physical events. Our results further indicate that motor-assisted imagery is not generally superior to perceptually driven dynamic imagery.

keywords: mental transformation, dynamic imagery, embodiment

Introduction

There is evidence that motor processes may influence children's spatial imagery (Funk, Brugger, and Wilkening, 2005; Frick, Daum, Walser, & Mast, 2009; Krüger & Krist, 2009a, 2009b; Schwarzer, Freitag, & Buckel, 2010) and may facilitate children's spatial cognition (Frick, Daum, Wilson, and Wilkening, 2009; Krist, Fieberg, & Wilkening, 1993; Rieser, Garing, & Young, 1994). A connection between the motor system and spatial imagery in children is also evidenced by the finding that motor training can positively influence performance in spatial imagery tasks (e.g., Jansen, Lange, & Heil, in press). In agreement with a Piagetian account (Piaget & Inhelder, 1967) some researchers have suggested that the motor system plays a larger role in children's than in adults' imagery (Funk et al., 2005; Frick, Daum, Walser et al., 2009; Frick, Daum, Wilson et al., 2009; for an overview, see Gibbs, 2005). In the following, we will present and discuss results from two experiments indicating that motor-assisted imagery is not necessarily superior to other forms of externally supported dynamic imagery in children.

For adults, Schwartz and Holton (2000, Exp. 2) have shown how performing a compatible motor activity may facilitate spatial imagery (see also Wohlschläger & Wohlschläger, 1998; Wohlschläger, 2001; and Wexler, Kosslyn, & Berthoz, 1998). Three differently colored pegs were placed on a small triangular pegboard. This pegboard was placed on a spool, so that participants were able to rotate the pegboard by pulling a string attached to the spool. Participants were asked to imagine how to bring two pegs into a given alignment and then to describe the spatial relation of another combination of two pegs. In one condition they had to rely on imagery only, in another condition they were instructed to actually rotate the pegboard by pulling the string. In both conditions participants had to keep their eyes shut. When pulling the string participants solved the task faster and their judgments were more accurate than in the pure imagery condition.

In a similar line of research, Simons and Wang (1998; Wang & Simons, 1999) assessed whether motor activity had a beneficial effect on dynamic imagery over and above corresponding passive movements. In a *spatial-updating* paradigm, adult participants were presented with an array of different objects. This array was then hidden from view and one of the objects was relocated. After the array had been hidden, participants either walked a specified path around the array or the array was rotated correspondingly. It turned out that accuracy in determining the relocated object was better when participants changed their position relative to the array than when the array was rotated. In two further experiments, the authors showed that it was not the motor activity per se that was responsible for this effect. When participants were passively moved around the (hidden) array in a wheeled chair, they performed as well as in the active movement condition.

Thus, opposed to theories of embodied cognition (cf. Wilson, 2002), Simons and Wang (1998; Wang & Simons, 1999) observed the same result for a task that did not involve any translocation of the participants but only a rotation of the array itself (as with Schwartz & Holton, 2000): It did not matter whether participants manually rotated the array by themselves or just watched its rotation.

Although Simons and Wang (1998; Wang & Simons, 1999) did not find any specific motor effect in either of their spatial-imagery tasks with adults, it may well be that children do exhibit such an effect in similar tasks. If so, this would provide support for a stronger link between motor activity and cognition in young children than in adults (cf. Frick, Daum, Walser et al., 2009; Funk et al., 2005; Frick, Daum, Wilson et al., 2009; Krüger & Krist, 2009a, 2009b). Alternatively, it is conceivable that there is no specific motor effect in children either, as long as there is a perceptual analogue to the external support provided by locomotion or manual actions.

As a previous study by Nardini, Burgess, Breckenridge, and Atkinson (2006) indicated that the original change detection task used by Simons and Wang (1998) might be too difficult for young children, we employed a simplified array-rotation task in the present research. Children were asked to track the rotation of a salient part of a concealed stimulus. We assumed that children would use some kind of covert simulation (imagery) to solve this task. Their imagery was assisted either by (a) perceptual input (perception condition), (b) by their own motor action (motor condition), or (c) not at all (pure imagery condition). In the perception condition, children watched the rotation of the array containing the stimulus, while, in the motor condition, they rotated the array themselves manually. In the pure imagery condition, children were asked to imagine the array rotating into a specified position. Assuming that the processes underlying spatial updating are similar in children and adults (cf. Wang & Simons, 1999), we expected that both kinds of external support, perceptual as well as motor, would facilitate children's spatial imagery as compared to the pure imagery condition.

Experiment 1

Method

Participants. A total of 72 children successfully completed the task (three children had to be replaced due to non-compliance). They were equally divided into two age-groups: kindergartners and third-graders. Among the kindergartners, there were 18 boys (mean age: 5 years, 11 months; *SD* = 7 months) and 18 girls (mean age: 5 years, 11 months; *SD* = 7 months). Among the third-graders, there were also 18 boys (mean age: 9 years, 4 months; *SD* = 5 months) and 18 girls (mean age: 9 years, 3 months; *SD* = 4 months).

Each child was tested individually in a suitable room of the respective kindergarten or school. Children were rewarded for their participation with a small rubber-stamp.

Materials. Thirteen different black and white drawings of animals and toys were used as stimuli (1 training stimulus, 12 test stimuli). On each drawing, one colorfully highlighted detail served as the target (e.g., Figure 1). Across the 12 test stimuli, the location of the target (0°, 90°, 180°, or 270°) as well as its color (red, blue, green, and yellow) were counterbalanced. Stimuli were presented on a rotatable circular board (38 cm in diameter) that was mounted on a quadratic board (60 cm edge length). A rod was horizontally protruding from under the circular board. There were four holes drilled in the quadratic board, into which rods could be planted vertically. The rotation of the circular board was blocked when the horizontal rod and a vertical rod met. These holes were allocated in such a way that the rotation could be stopped every 90° (see Figure 2). There was also a cover used to conceal the stimuli. A pile of circular sheets of paper for registering children’s answers was affixed to this cover. On each trial, a new sheet of paper was used by removing the previous one from the pile.

Procedure. Children were randomly assigned to one of three experimental conditions: motor, perception, or pure imagery.

At the start of each session, children were seated in front of the apparatus. A rod was planted in the left hole of the quadratic board (9 o’clock position; see Figure 2) and the circular board was rotated until its horizontal rod touched the vertical rod of the quadratic board. This was the initial position for all further training and test trials. Rotations were always performed counterclockwise.

Training. The training stimulus (a portrait of a clown wearing a hat with a red flower) was placed on the circular board and the target (the red flower) was indicated. Then, the stimulus was covered and children were asked to point to the target by touching the correct spot on the cover. This position was marked by the experimenter (using a stamp of the same color as the target). Next, the cover was removed to reveal the actual position of the target. After the drawing had been covered again, the procedure for the training and test trials varied according to the experimental condition.

In the *motor condition* children were instructed to rotate the circular board about 360°. After the rotation, the course of action was identical to the first training trial: The child was asked to point to the target, the position was marked, and visual feedback concerning the target location was given. This procedure was repeated with a rotation about 135°.

The *perception condition* was identical to the motor condition, except that the board was rotated by the experimenter.

In the *pure imagery condition*, children had to predict the target's position, before the stimulus was covered and rotated by 360°. Again, this was repeated with a rotation about 135°. Otherwise, the procedure was the same as in the other two conditions.

In all conditions, children were asked whether they had understood the task. If they denied this or were unsure, the training was repeated once.

Test. For the test trials, rotation angles of 90°, 180°, and 270° were used by positioning the vertical rod at 6 o'clock, 3 o'clock, and 12 o'clock, respectively. Each of the 12 test drawings was rotated by these angles in a block of three trials, yielding a total of 36 trials per child. Both, the order of the stimuli as well as the order of the angles, by which each stimulus was rotated, were randomized. In the motor condition children rotated the circular board themselves, in the perception condition the board was rotated by the experimenter, and in the pure imagery condition the board was not rotated at all. No feedback was given during the test.

Results

The target deviations produced by each child were calculated in angular degrees (absolute errors). These were averaged across the 12 test stimuli yielding a mean target deviation for each angle of rotation. The resulting mean target deviations were submitted to a 3 (*angle*s: 90°, 180°, and 270°) x 3 (*condition*s: motor, perception, and pure imagery) x 2 (*age*: kindergarten vs. third grade) x 2 (*sex*) ANOVA with repeated measures on the first variable.

There was a significant main effect of angle, $F(2, 120) = 19.46$, $p < .001$, $\eta^2 = .25$. The mean target deviation rose with the angular difference (90°: $M = 52°$, $SD = 28°$; 180°: $M = 61°$, $SD = 32°$; and 270°: $M = 65°$, $SD = 27°$). The linear component of the angle effect turned out to be highly significant, $F(1, 60) = 32.46$, $p < .001$, $\eta^2 = .35$, and there was no quadratic trend, $p > .10$.

Kindergartners produced a greater mean deviation (*M* = 70°, *SD* = 26°) than third-graders (*M* = 48°, *SD* = 26°), *F*(1, 60) = 14.41, $p < .001$, $\eta^2 = .19$, but there was no significant interaction involving age, all $F < 1$.

There was also a significant condition effect, *F*(2, 60) = 7.46, $p = .001$, $\eta^2 = .20$, but no interactions involving condition, all $F < 1$. Planned t-tests revealed, that performance did not differ between the motor (*M* = 55°, *SD* = 27°) and the perception condition (*M* = 48°, *SD* = 28°), *t*(46) = 0.9, $p = .38$, $d = 0.26$, whereas performance in both conditions combined (*M* = 52°, *SD* = 27°) was significantly better than in the pure imagery condition (*M* = 74°, *SD* = 22°), *t*(70) = 3.46, $p = .001$, $d = 0.89$.

Finally, there was a three-way interaction between angle, condition, and sex, *F*(4, 120) = 2.49, $p < .05$, $\eta^2 = .08$. To disentangle this interaction, two additional 3 (*angle*) x 3 (*condition*) x 2 (*age*) ANOVAs were computed separately for both sexes. A significant angle by condition interaction was only found for the boys, *F*(4, 60) = 2.97, $p < .05$, $\eta^2 = .17$, but not for the girls, $F < 1$. An inspection of the corresponding graphs indicated that, contrary to the overall trend described above, boys exhibited no angle effect in the pure imagery condition.

Discussion

Unsurprisingly, older children (third-graders) performed better than the younger ones (kindergartners) in terms of average target deviation produced. There was, however, no indication of a developmental change concerning the influence of motor activity on children's spatial imagery; in particular, there was no significant age by condition interaction. Both age groups benefited from external support as compared to the pure imagery condition, but it did not make any difference whether children's spatial imagery was externally supported perceptually or by their own motor activity.

Errors tended to increase linearly with angular disparity. This result suggests that children were indeed trying to solve the task by mentally rotating the respective drawing or target and not by using an analytic strategy (see below) or mere guesswork. That might not be true for the boys tested in the pure imagery condition: The missing angle effect suggests that they relied on guessing.

Whether or not children exhibited an angle effect is thus indicative of the solution strategy employed by them. At least in principal, children could have attended to a landmark that was moving in alignment with the target and tried to remember the spatial relation of those two points. The horizontal rod protruding from the circular board was a likely candidate for this strategy. Yet, if children had used such an analytic strategy, a linear trend should not have surfaced, because the ability to reproduce the spatial relation of two points on the array should not depend on the amount of rotation of the array.

While suggesting a non-analytic strategy, the angle effect itself does not unequivocally indicate the exact strategy children tended to use in our task. There is empirical evidence that imagery can be supported by eye movements tracking the presumed motion of a hidden object. Huber and Krist (2004) asked adults to determine the landing point of a ball pushed off a horizontal platform. The actual flight of the ball was hidden from view, so participants had to base their judgment on the perceived speed of the ball, when it left the platform. It turned out that those participants who supported their imagery of the flight path with corresponding eye movements were more accurate in judging when and where the ball was going to land compared to those who did not show such a behavior (for a similar result obtained with kindergartners, see Wilkening, 1981).

It is therefore conceivable that, to keep track of the target's position, children capitalized on the external facilitation (i.e., the rotation of the array) by following the target's assumed movement with their eyes. However, if children actually used such a strategy in our motor and perception conditions, they would have been disadvantaged in the motor condition, because they had to break their fixation to be able to rotate the board manually. This was not true for the perception condition, where the experimenter rotated the board and children could have kept their fixation. This problem was addressed in Experiment 2.

Experiment 2

Experiment 2 was a replication of the perception and motor conditions of Experiment 1 with one modification: To compensate for the fact that, in the motor condition of the previous experiment, children could hardly keep their eye gaze fixated on the target when they had to reach for the board, children now had to execute a visually controlled reaching movement in the perception condition, too. A bell was placed next to the round board. This bell was sounded by pushing a button on its top. Children were told that the experimenter would start rotating the board after they had hit the bell. Therefore, in the motor condition a glance was needed to guide the hand to the board and in the perception condition to guide the hand to the bell. Informal observations validated that children did not keep their eyes fixated on the cover in either condition.

Method

Participants. Forty-nine kindergartners aged 5 to 6 years were recruited for the study. Twenty-five of the children were boys (mean age: 5 years, 11 months; *SD* = 5 months) and 24 were girls (mean age: 5 years, 10 months; *SD* = 6 months).

All children were tested in their respective kindergartens. Materials and procedure were the same as in Experiment 1, except for the following modifications.

Materials. The same apparatus and stimuli as in Experiment 1 were used in Experiment 2, except that a bell was added in the perception condition.

Procedure. Children were randomly assigned to one of two experimental conditions: a motor condition and a (modified) perception condition. Unlike Experiment 1, there was no pure imagery condition in Experiment 2. The procedure for the motor condition was exactly the same as in Experiment 1. The procedure for the perception condition was changed in one detail only: During each trial children had to strike a bell before the experimenter started the rotation. Children were told that this was necessary to inform the experimenter that they were ready.

Results and Discussion

Data were aggregated as in Experiment 1 and submitted to a 3 (*angle*s: 90°, 180°, and 270°) x 2 (*condition*s: motor, perception) x 2 (*sex*) ANOVA with repeated measures on the first variable.

As in Experiment 1, there was a significant main effect of angle, $F(2, 90) = 21.92$, $p < .001$, $\eta^2 = .33$, and no interaction of angle and condition, $F < 1$. Again, the deviation from the intended target rose with the angular difference (90°: $M = 56°$, $SD = 23°$; 180°: $M = 67°$, $SD = 23°$; and 270°: $M = 73°$, $SD = 22°$). This was validated by a significant linear trend, $F(1, 45) = 34.77$, $p < .001$, $\eta^2 = .44$, but no quadratic trend, $p > 10$, indicating that children used a non-analytic strategy.

Descriptively the modification of the perception condition led to a somewhat better performance in the motor condition than in the perception condition (see Table 1). This difference failed to reach significance, however, $F(1, 45) = 1.72$, $p = .20$. The same was true for the angle by condition and the sex by condition interaction, both $F < 1$.

General Discussion

In Experiment 1, children performed worse in the pure imagery condition than in both the perception and the motor condition. In hindsight, the imagery instruction given in Experiment 1 might have been insufficient, as there are examples of even younger children successfully using dynamic imagery to solve a task after receiving an elaborated imagery instruction (e.g., Joh, Jaswal, & Keen, 2011). In our case, an explicit instruction to follow a presumed path of the target might have improved children’s performance. On the other hand, it was to be expected from the beginning that children would perform better in a dynamic imagery task externally supported by actual rotation than in a pure imagery task.

More important is the finding that it did not matter how external support was provided. Neither in the original nor in the control experiment, there was a significant difference between the motor and the perception condition. As in comparable studies with adults (Simons and Wang 1998; Wang & Simons, 1999), no motor specific influence on children's capability of mental transformation was discernable. These findings are not in agreement with a strict Piagetian view according to which cognition evolves from motor action ontogenetically (Piaget, 1976, 1978), as favored by authors who found stronger effect sizes concerning motor effects in children than in adults (Funk et al., 2005), or were able to demonstrate motor effects in younger children that were absent in older children and adults (Frick, Daum, Walser et al., 2009; Frick, Daum, Wilson et al., 2009).

By no means do we propose that there is no qualitatively different link between imagery and motor processes in younger children compared to older children and adults. Such a qualitatively different link was suggested by our earlier research (Krüger & Krist, 2009a, 2009b) relying on a mental rotation paradigm (cf. Funk et al. 2005). Motor effects (i.e., influences of biomechanical constraints) on imagery were found in adults as well as in children, but the variables triggering the manifestation of such effects differed between younger children and older children or adults. Additionally, these effects were more stable in older children and adults.

The theoretical framework of *timing-responsive representations* (Schwartz & Black, 1999; Schwartz & Holton, 2000; cf. Huber & Krist, 2004) might be useful to reconcile the present findings with previous research on motor effects in children: On this account, mental transformations of a certain type of mental representations, termed timing-responsive representations, depend on signals indicating change. In other words, every step of a dynamic imagery process is controlled by a timing signal updating a particular timing-responsive representation. While motor action can provide such signals, timing signals can also be provided by other sources, particularly by dynamic visual input.

An alternative explanation for the present finding that children benefited equally from motor and perceptual support when imagining target rotations, may be derived from the assumption of joint usage of neural resources (cf. Wilson, 2002): If – at least partially - the same neural structures are responsible for motor actions, such as reaching and crawling, and mental transformations, it would be plausible that motor actions and corresponding mental transformations develop at the same time in human development. A theoretical approach that encompasses joint usage of neural resources is *common coding* (cf. Prinz, 1990). Here, a close connection is supposed between conducting a motor action and observing the same motor action in another individual. This in turn is specified by the model of a *mirror neuron network* (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). According to this model, observed motor actions are coded in exactly the same motor areas that are responsible for planning and executing a corresponding action. Common coding and mirror neurons would explain that there is a comparable outcome when participants perform a motor action or observe a similar motor action. Manually rotating the array or observing it being rotated by the experimenter should therefore produce largely the same type of external support. This particular hypothesis could be tested by contrasting the present perception condition, in which the array is rotated by a human experimenter, with a modified perception condition, in which it is rotated by a machine. Further research is clearly needed to address this issue as well as to shed more light on the more general issue of the developmental fate of the link between perception, action, and cognition.

To conclude, while kindergartners' dynamic imagery can be facilitated by compatible motor actions, there is no need to assume that it is still tightly and exclusively coupled to motor processes. In Experiment 1, external support provided by both motor action and perception was superior to no such support, but there was no evidence that motor action was superior to perception regarding its impact on children's performance.

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Table 1

Mean Target Deviations (and Standard Deviations) for the Kindergartners (5 to 6 years old) in Experiments 1 and 2.

Condition	Experiment 1		Experiment 2	
	M	*SD*	*M*	*SD*
Motor action	64°	26°	61°	20°
Perception[a]	57°	27°	69°	19°

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[a] Note that the perception condition differed between experiments

Figure Captions

Figure 1. Examples of drawings and targets used in Experiments 1 and 2. Targets are the rabbit's tail (yellow) and the doll's left shoe (blue).

Figure 2. The apparatus used in Experiment 1 and 2. The rotating board was fitted with a horizontal and a vertical rod (highlighted). These served as mechanical stops (i.e., the circular board was rotated until it was arrested by the vertical rod); in the pure imagery condition (Exp 1), they indicated the possible rotation of the board. The board was covered with a checkered pattern to make the rotation more perceptible. Pictures were affixed on top of the board and covered. The cover was also used to hold the paper sheets that were in turn used by the experimenter to mark the children's answers.

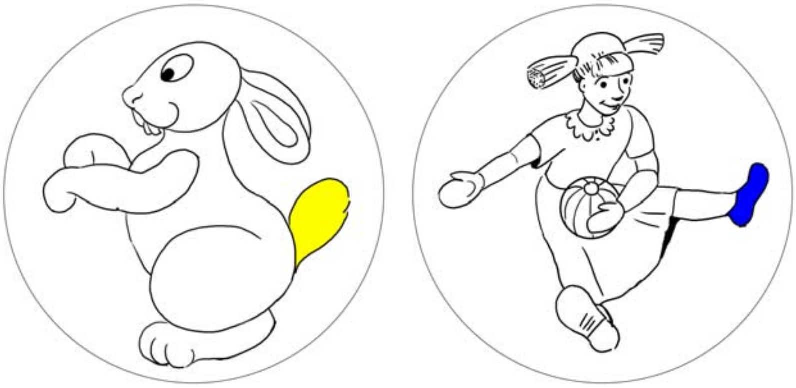

Figure 1

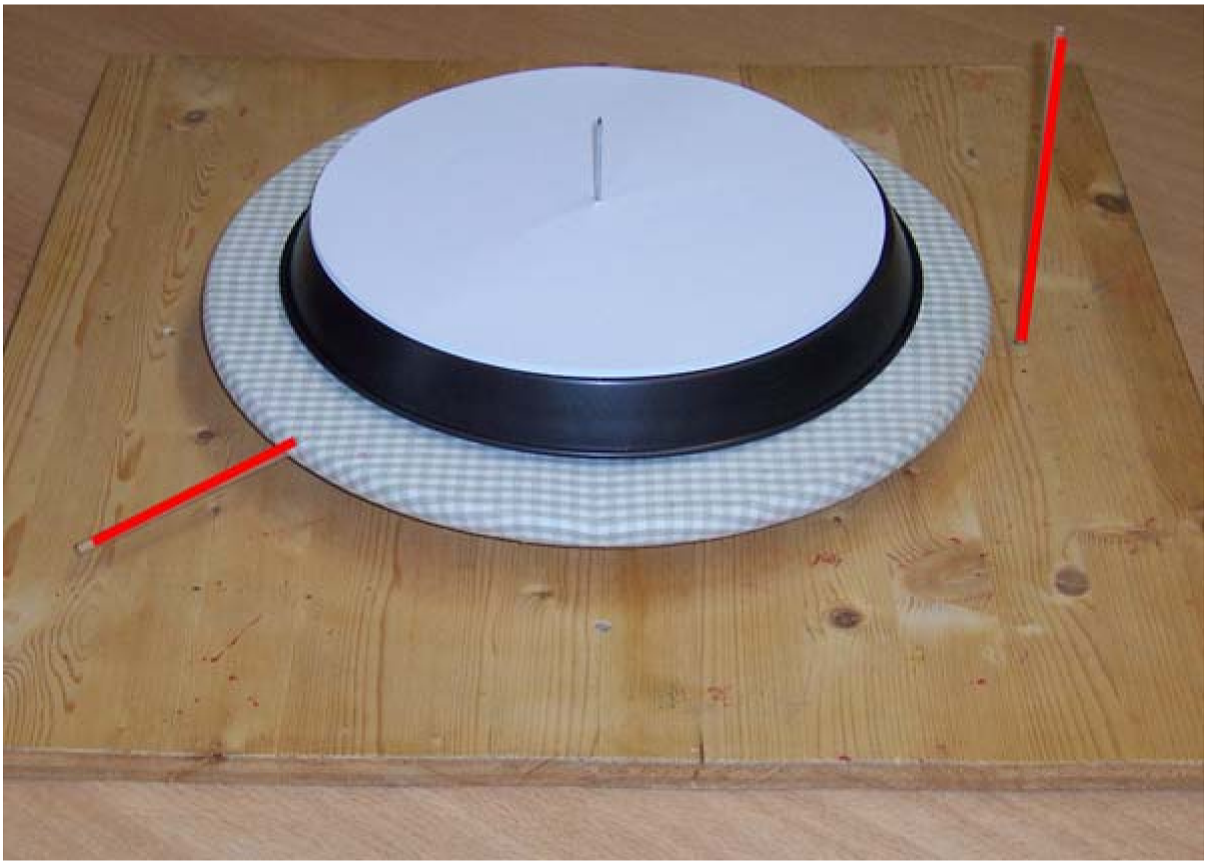

Figure 2

Highlights

Children's dynamic imagery was found to be facilitated by motor processes as well as by perceptual support.

We propose that dynamic imagery is guided by timing-responsive representations in both children and adults.

The present results cast serious doubts on a radical embodiment view of human cognition according to which motor processes should play a privileged role both functionally and ontogenetically.