Analogue Mental Transformations in Three-year-olds: Introducing a New Mental Rotation Paradigm Suitable for Young Children

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I wish to thank Marlen Kaiser for assistance in data collection, Wolfgang Bartels for programming, Heidrun and Lutz Krüger for proof-reading, and Horst Krist and Georg Jahn for useful comments. This research was supported by Grant KR-1213/3-1 from the Deutsche Forschungsgemeinschaft (DFG).

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Abstract

Until now successful application of the mental rotation paradigm was restricted to children aged five years or older. By contrast, recent findings suggest that even infants can perform mental rotation. Unlike the methods used in infant studies, the new mental rotation task used in this study allows for the measurement and interpretation of reaction times. Three-year-old children were presented with a stimulus configuration on a touchscreen and asked to bring a rotated stimulus into an upright position using the shortest path. Mean reaction time increased linearly with angular disparity. This result is interpreted as evidence for an analogue mental transformation in three-year-olds as reported in mental rotation in older children and adults.

Keywords: mental rotation, mental transformation, cognitive development, imagery, analogue mental representations

Introduction

The mental rotation paradigm (Shepard & Metzler, 1971) entered developmental psychology with a seminal article by Marmor (1975) describing mental rotation in five-year-old children. Not only did Marmor establish the fact that five-year-olds were able to perform dynamic mental transformation, but she was also able to demonstrate that the underlying cognitive processes in children resembled those of adults. That was possible by interpreting children's reaction times (RT): As in adults, mean RT rose linearly with the angular disparity between the presented stimuli pairs. This linear relation is commonly seen as evidence for participants engaging in an analogue mental transformation of one of the stimuli - the further the stimulus has to be rotated mentally, the longer the duration of the process.

The mental rotation paradigm has been used extensively in developmental psychology since. It seems that four-year-old children lack the ability to solve mental rotation tasks. A recent example is a study by Quaiser-Pohl, Rohe, and Amberger (2010). The authors used a modified Vandenberg and Kuse (1978; cf. Peters et al., 1995) task to identify solution strategies in children. Instead of abstract geometrical figures, child-oriented pictures of humans and animals were used as stimulus material. Children were always presented with one exemplary stimulus which was not rotated. This stimulus was to be compared with two distractors and one target stimulus, all presented simultaneously in a serial configuration. Distractors were always mirror images of the exemplary stimulus while the target was congruent with the exemplary stimulus. Distractors and targets were presented rotated in the picture plane. The task was to identify the target stimulus. While children older than five years of age were generally able to solve this task, younger children seemed unable to do so. Their solution strategies reflected their inability: They relied on guesswork and/ or compared irrelevant features of the stimuli.

This negative finding contrasts with results from recent infant studies using a habituation-dishabituation paradigm. Infants displayed abilities that can be interpreted as the first beginnings of the mental transformations necessary for mental rotation. In two independent studies Moore and Johnson (2008) and Quinn and Liben (2008) tested 4 and 5 months old infants (cf. Schwarzer, Freitag, & Buckel, 2010). During habituation, participants were presented with animations of rotating stimuli. In the test, male infants preferred the mirror images to the original stimuli, although both were presented at a new - hitherto not shown – angle of rotation. Thus, according to the authors, these infants had to continue the presented rotation mentally and thereby performed mental rotation. Alternatively, these results might be attributed to an interpolation process, bridging the relatively short angular disparity between the ending of the displayed rotation and the test stimuli.

Such concerns are invalidated by findings by Mash, Arterberry, and Bornstein (2008; cf. Bower, 1966). They tested five months old infants with static stimuli. During habituation, an abstract stimulus was presented repeatedly, but from different perspectives. These perspectives were arranged as rotations about a specific axis. In the actual test, the original stimulus (e.g., a cuboid with a pyramid and a cube on top) or an unfamiliar similar stimulus (e.g., a cylinder with a pyramid and a cube on top) was presented from a new perspective that represented a rotation about a different axis than that during habituation. Therefore simple interpolation was eliminated. Still, infants preferred the unfamiliar stimulus in this study, too. Thus, they were able to recognize the familiar stimulus, although seen from a completely different perspective. This implies a mental transformation.

Apparently, there seems to be quite a rift between the competent infants and the failing kindergartners (cf. Keen, 2003; Krist, 2010). The aim of the present research was to reduce this gap. Therefore, a research method was developed that not only allowed children as young as three years of age to demonstrate their mental rotation ability, but that also allowed to measure RT during this process.

To this end, participants were confronted with a simplified mental rotation test. Instead of asking participants to judge whether stimuli of a given set are congruent (cf. Shepard &

Metzler, 1971), children were asked to bring a stimulus in an upright position by rotating it on the shortest path. It was presumed that participants perform a mental transformation identical to that in mental rotation tests before actually rotating the stimulus. The time needed to make this transformation should be analogous to the RT in standard mental rotation tests. As predicted, a linear connection between angular disparity and RT, typical for mental rotation, was observed.

Method

Participants

A total of 43 three-year-olds were recruited for the study. Three of these children did not finish the test. One child was excluded for not being fluent in the German language. Of the remaining 39 children, 24 were boys (M = 42.2 months, SD = 3.28) and 15 were girls (M = 42.2 months, SD = 3.75). Children were tested individually in a quiet room in their kindergarten. They were not aware of the goal of the study and had not partaken in a similar experiment before. All children were rewarded with a medal for their participation.

Materials

The stimulus material consisted of 18 initially hand drawn pictures that were digitalized (512x512 pixel, jpeg). The pictures were designed to have an unambiguous top side as children were asked to bring them into the “right” alignment. In digital postprocessing, a round background was pasted under all motives to prevent nooks and edges from giving any cues about the alignment. All the pictures were rotated into seven different angles (45°, 90°, 135°, 180°, 225°, 270°, and 315°). Stimuli were presented on an Elo Touchsystems 1928L touchscreen (19”, 1280x1024 pixel). E-Prime software running on a Fujitsu-Siemens Amilo Pi 1556 laptop was used for presentation and data collection. An example of a stimulus configuration can be seen in Figure 1.

Procedure

Stimuli were always presented in pairs. Unlike the classical mental rotation task (cf. Shepard & Metzler, 1971), both stimuli were always congruent. One stimulus was not rotated (target stimulus) while the other one was rotated clockwise about 45°, 90°, 135°, 180°, 225°, 270°, or 315° (test stimulus). Participants were asked to straighten the test stimulus (that way it would also be congruent with the unrotated target stimulus) by rotating it the shortest path. When – for example – the test stimulus was rotated about 90° it would be considered as a correct solution to rotate the stimulus 90° counter clockwise and as an incorrect solution to rotate it 270° clockwise (for the 180° tasks there was no correct or incorrect solution). The trial always ended when the test stimulus reached the target position.

Children were seated facing the touchscreen. In front of the screen was the outline of a pair of hands and children were told to place their hands on these outlines before every trial if they did not do so on their own. The experiment was divided into training and test.

Training consisted of nine trials and started with the experimenter explaining the function of the touchscreen. The experimenter solved the first two trials while children were watching. In both of these trials the test stimuli were rotated about 180°. The experimenter demonstrated that the test stimuli could be rotated by touching the screen on the virtual “handle” surrounding the stimuli picture and dragging the picture along by the handle. Then, in the first trial, the experimenter rotated the test stimulus clockwise about 180° and in the second trial about 180° counterclockwise. The direction of the rotation was switched on every other trial. In the seven trials that followed children were asked to rotate the test stimuli by themselves. If children made a mistake (i.e., not choosing the shortest path) the respective trial and the instruction to use the shortest path were repeated once. If children then made the same mistake again all seven training trials were repeated once.

The test consisted of 14 trials divided into two blocks. Fourteen different stimulus pairs were presented in a random order. In the first block, seven test stimuli were presented rotated about all the seven different angles. This was repeated in the second block with another set of motives. Precisely as in the training part, children were asked to adjust the test stimuli, but no trials were repeated and no help or further instructions were given.

Results

Number of Correct Solutions

As a first step, performance was tested on a group level against an expected chance level of 6 correct trials. Participants completed 14 trials in the test, but two of these consisted of a rotation about 180° and thus did not have a correct solution (i.e., shorter path). Therefore, these two trials were not considered in this analysis of error scores. Group performance was indeed significantly above chance: M = 8.28 correct (out of 12), SD = 0.37, $t(38) = 6.18$, $p < .001$.

Reaction Times

Although the analysis of the number of correct solutions indicated that participants were generally up to the task at hand, for the analysis of the RT only those participants were considered who actually performed above chance on an individual level. Participants that did not perform significantly above chance ($\alpha = 0.10$) in accordance to a binomial distribution were excluded from further analysis. According to this criterion, children needed 9 or more hits. Children who did not reach this criterion were excluded from further analysis. This led to the exclusion of 21 children (16 boys and 5 girls).

The data of the remaining 18 children (M = 43.2 months, SD = 2.79) were included in the RT analysis. The RT measure was defined as the time needed by participants to touch the screen after stimulus onset. RT were averaged across the four complementary angles (45° and 315°, 90° and 270°, 135° and 225°, and 180°) and their repetitions (in test block 1 and 2). A 4 (Angles of Rotation) x 2 (Sex) ANOVA was computed.

A marginally significant effect was found for the variable angle of rotation, $F(3, 48) = 2.40$, $p = .08$, $\eta^2 = .13$. Planned contrasts revealed that this reflected a linear relation between

RT and angular disparity as expected in mental rotation tasks (see Figure 2), linear trend: $F(1, 16) = 11.45$, $p = .004$, $\eta^2 = .42$.

Discussion

In the present simplified mental rotation task, 3-year-olds did not only perform above chance on a group level, but there was also a substantial number of children who performed above chance on an individual level. A linear relation between angular disparity and RT, indicating analogue mental transformation in mental rotation tasks, was established. These results bridge the gap between findings from infant studies (Quinn & Liben, 2008; Moore & Johnson, 2008; and Mash, Arterberry, & Bornstein, 2008) and studies with kindergartners (Marmor, 1975; and Quaiser-Pohl, Rohe, & Amberger, 2010).

The present task is not identical to classic mental rotation tasks (cf. Shepard & Metzler, 1971). Similar as in infant studies, task demands were reduced considerably as compared to the classical paradigm to make the task feasible for 3-year-olds. No direct comparison of stimuli was required and children could actually rotate the stimulus material. The dynamic and interactive task format might have induced a motor-assisted solution strategy (cf. Kosslyn, Thompson, Wraga, & Alpert, 2001). Therefore, the observed linear RT curve could represent the time needed for movement planning: At least under certain circumstances, the time needed to plan a movement is related to the time needed to perform the movement (Rosenbaum & Krist, 1996). Therefore, the observed linear trend could be caused by children's movement planning, because a higher angular disparity involves a longer manual rotation of the stimulus. Yet, interpretations in terms of mental transformation and motor planning are not mutually exclusive per se: There is evidence that imagery processes underlying mental rotation may be rooted in movement planning (Kosslyn, Ganis, & Thompson, 2001). Some authors even describe mental rotation as covered action (Wohlschläger & Wohlschläger, 1998; Wohlschläger, 2001; cf. Wexler, Kosslyn, & Berthoz, 1998). Therefore it might not be reasonable to separate movement planning from mental transformation. In any case, attributing the RT results to movement planning alone would not explain how participants knew in which direction they had to rotate in the first place.

This brings us back to the first point that no stimulus comparison was required in the present task. One might speculate that adult participants instantly “see” the shorter rotation angle when trying to bring two stimuli into alignment in a mental rotation task (cf. the notion of preattentive processing, Parsons, 1997; Sekiyama, 1982; Cohen & Kubovy, 1993). If this is the case, an imagery process causing a linear RT trend can only take place thereafter: By an analogue mental transformation, one stimulus is brought into alignment with the other one to assess their congruency.

Concerning the present task, the following scenario ensues from this speculation: Children may realize the shortest path instantly, as adults do. Therefore, a mental transformation process is not strictly necessary. After realizing the shortest path no further stimulus processing is needed - children could just start to manually rotate the stimulus in the apprehended direction. Yet, three-year-olds may fall back to a redundant imagery process mirroring the upcoming action to verify their realization and, thereby, produce the linear RT trend. Still, this would include an analogue mental transformation similar to mental rotation in adults.

Conclusion

The evaluation of the new method was successful: Not only were three-year-old children able to solve the simplified mental rotation task, but there was also a linear relation between RT and angular disparity suggesting an analogue mental transformation. More research is required concerning differences between tasks used for infants, the present task, and tasks presented to older children and adults – nevertheless, the present findings are in accordance with the assumption of adult-like mental rotation capabilities in three-year-olds.

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Figure Captions

Figure 1

Example of a stimulus configuration: Participants were asked to “straighten out” the rotated stimulus. The correct solution would be to rotate the right teddy bear about 90° clockwise. Therefore, children would touch the handle placed around the right stimulus and drag the bear along.

Figure 2

Mean RT (and standard errors) as a function of angle of rotation.

Figure 1

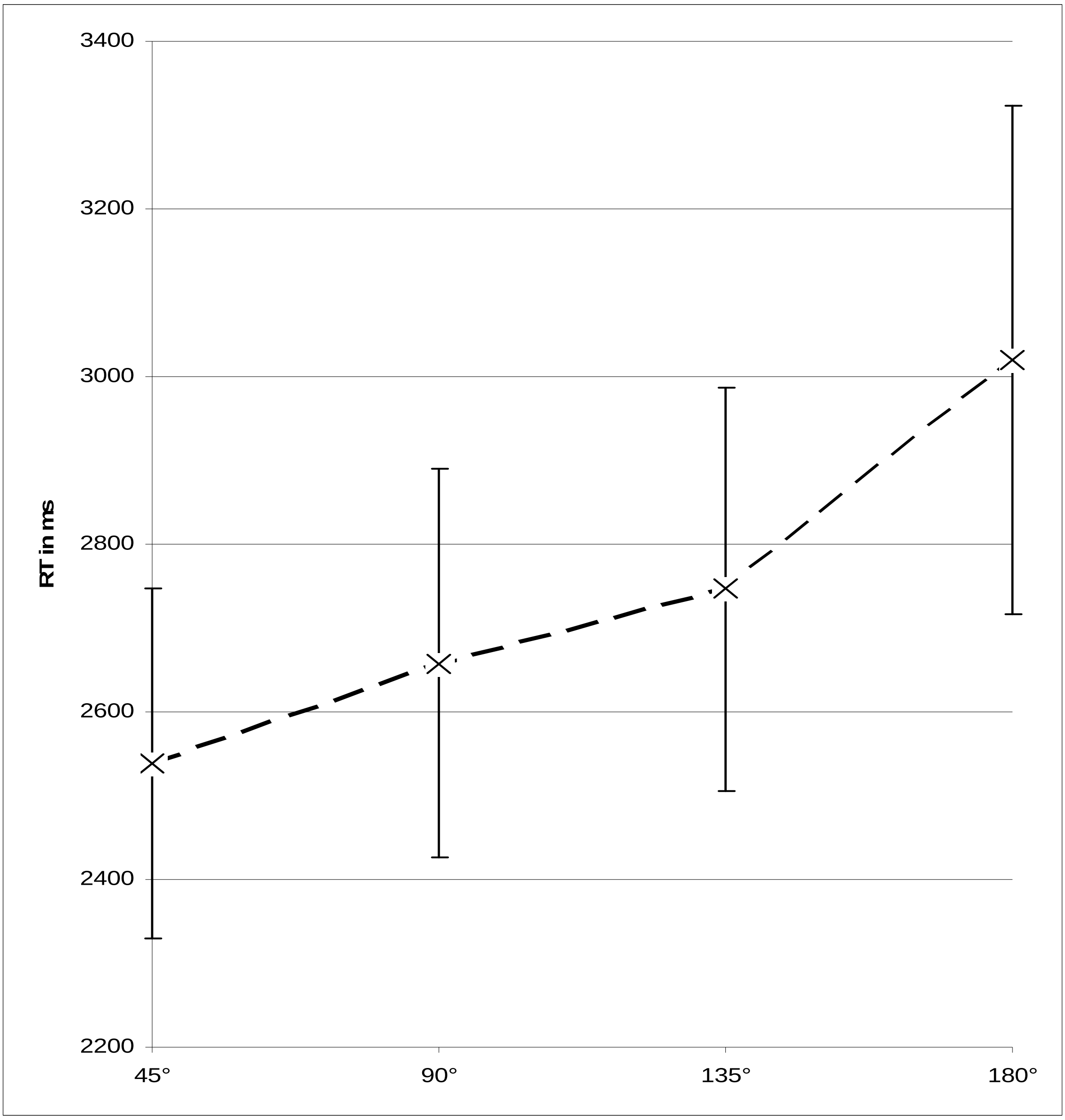

Figure 2

Highlights:

Success in a task similar to mental rotation above chance in three-year-olds.

Many three-year-olds perform above chance on an individual level.

Linear trend indicates analogue transformations in three-year-olds.

Linear trend indicates mental rotation in three-year-olds.