The Malleability of Children’s Mental Rotation Strategies: What do children’s mental rotation tests really measure?

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Abstract

The most commonly used measure of spatial cognition to assess both adults and children is mental rotation. However, little is known about the cognitive strategies that children use to solve this task. Understanding how and when children may employ different mental rotation strategies can illuminate the development of mental rotation ability and help clarify previous mixed findings on the developmental trajectory of children's mental rotation skills. Thus, in this study, we investigated what strategies children use in a new mental rotation task and whether their strategy use would be influenced by the test instructions. In Experiment 1, we found that the types of strategies children used in our mental rotation test differed from strategies reported in previous research, suggesting that strategy use is dependent on test design. In Experiment 2, we found that children's strategy use can be malleable; changing the test instructions reduced one type of erroneous strategy, flipping. Our findings suggest that different tests labeled “mental rotation tests” may actually be measuring different abilities.

Keywords: mental rotation; spatial cognition; cognitive development; strategy; assessment

Introduction

Mental rotation is the most commonly used assessment of spatial thinking for both adults and children (Uttal et al., 2024). The majority of tests are based on Shepard and Metzler’s (1971) research, in which participants were asked to mentally visualize the rotation of 3D cube figure stimuli. Notably, participants in the original Shepard and Metzler mental rotation study were explicitly instructed to imagine rotating the stimuli. However, the specific instructions given during a mental rotation test can vary regarding whether participants are told how to solve the problem. Further, adults do not always visualize rotation when solving mental rotation problems (Hegarty, 2017; Just & Carpenter, 1985). Instead, some individuals may use more analytic strategies to determine the answer, such as focusing on relative angles within the stimuli instead of rotating the stimuli.

Despite the importance of understanding strategy use when interpreting mental rotation test results, there has been very little research on children’s mental rotation strategy use. In one of the few studies that have investigated children’s mental rotation strategies, Quaiser-Pohl and colleagues (2010) reported that young children tend to use inappropriate strategies on the Picture Rotation Test, a commonly used mental rotation test for young children. Children are presented with a target animal stimulus and three answer choices. The answer choices are identical to the target stimulus, except that the two incorrect answers are mirror reflections of the target stimulus. Each of the three answer choices is rotated a different amount. Children reported strategies that the researchers deemed inappropriate because these strategies did not address task demands. In other words, these strategies did not result in children correctly solving the rotation problem. For example, some children reported using the gaze direction of the answer choice stimuli. The children using this strategy would select their answer based on whether the answer choice was looking in the same direction as the target animal, even if this answer choice did not match the target. Thus, this strategy does not result in the correct answer for most questions. The researchers suggested that the use of these inappropriate strategies may explain why young children tend to perform poorly on mental rotation tests.

Interestingly, some of the “inappropriate” strategies reported by children in Quaiser-Pohl et al.’s (2010) study seem dependent on the specific mental rotation test they used. The instructions of the Picture Rotation Test use animal gaze to demonstrate to children how to identify the difference between mirror reflections (Quaiser-Pohl, 2003). Therefore, children who focused on where the animals were looking might have been confused regarding what was being asked of them during the test. Furthermore, another strategy reported in this study involved children choosing whichever answer choice was the most upright. This upright strategy is only possible when the answer choices are rotated different amounts relative to each other. Thus, this strategy would not be feasible on other mental rotation tests, such as those wherein individuals make a same/different judgment between two stimuli. In summary, test design and instructions for children's mental rotation tests may influence children’s strategy usage.

The main goal of this paper is to investigate the effects of mental rotation test design and instructions on children’s mental rotation strategy use. To achieve this goal, we have broken our goal into two main questions.

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1. What strategies do children use on a different mental rotation test than the Picture Rotation Test?
2. Do the instructions given for a mental rotation test affect children's strategy usage, and if so, how?

To answer the first research question, in Experiment 1 we gave children a mental rotation test that uses a different paradigm than the Picture Rotation Test and asked them to report the strategies they used during the test. We hypothesized that the children would report different strategies compared to those found in the Quaiser-Pohl et al. (2010) study. Specifically, we hypothesized that we would not observe the test-dependent strategies identified in their study and will instead discover new strategies specific to our test paradigm.

To answer our second research question, we used a between-subjects design to test if different instructions would lead to different reported strategies. We used spatial language to differentiate two conditions. In the *spatial language* condition, children received instructions that used specific language such as "turn," "rotate," and "upside down." In the *control condition*, the instructions were vaguer and described "moving" the stimuli. Since the explicit use of the term "rotation" may guide children to use more rotation-based strategies, we hypothesized that children in the spatial language condition would report more rotation-based strategies than those in the control condition.

Experiment 1

Methods

Participants Children were recruited and participated online through the LookIt platform (Scott & Schulz, 2017). A total of 103 children between the ages of 4.5-to-7 years-old participated. Some children were dropped for either not completing the study (*n* = 8), being outside the age range (*n* = 1), or for having missing data due to technical errors (*n* = 9). Thus, our final sample consisted of 85 children, with a mean age of 5.55 years (SD = 0.73, range = 4.52 to 6.82, 36 females).

Design, Measures, and Procedure A new mental rotation test was designed for this study that is similar to the Ghost mental rotation test (Frick et al., 2013). The test consists of three practice questions and 21 test items. This paradigm was chosen because it differs in specific ways from those used in previous research on children's mental rotation strategies. In the present paradigm, children are shown a silhouette of a sea creature and two answer choices. One answer choice can be rotated to fit perfectly over the silhouette, while the other answer choice is a mirror reflection and would not fit the silhouette even if rotated. Thus, the chance level for this test is calculated to be 10.5, since each item has a 50% chance level.

Before the practice questions, children watched a short, animated video that described the task and demonstrated a mermaid character solving two items, one with no rotation and one with 180° rotation. The video featured an animated mermaid who explained to the child that they were going to play a matching game. The version of the video children saw was dependent on which condition they were in. Children were randomly assigned to the spatial language condition or the control condition once starting the study. There were 41 children in the control condition and 44 children in the spatial language condition. The exact language in the instructional video was different between conditions, but the visuals were the same. In the *spatial language condition*, the video included instructions to imagine rotating the sea creature pictures. In the *control condition* the video included more vague instructions to imagine moving the picture. For example, during the part of the video where the mermaid is demonstrating rotating a seahorse to see if it fits the silhouette, the children in the spatial language condition heard that they "will *turn* the seahorse on the *left"*, while children in the control condition heard that they "will *move this* seahorse". Each sentence of the instructions was matched across the two conditions to minimize difference in overall length and number of words. In addition to explicit instructions to "turn" the sea creatures, the spatial language condition also used language such as "upside down" when described rotated sea creatures and emphasized "fitting" the pieces. In contrast, the control condition language used the more general phrase "topsy turvy" and focused on matching the pieces instead of fitting the pieces.

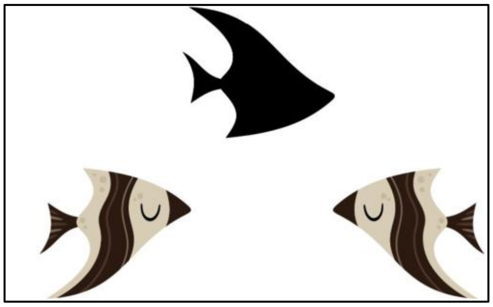

Figure 1. Example Item from Fish Mental Rotation Test

After the instructional video, all children completed the practice questions and received feedback on their answers. If the child chose the wrong answer during a practice trial, they were instructed that their answer could not match the silhouette and were asked to try the other answer choice. There were 21 unique test items, with three questions for each of seven orientations (0°, 30°, 60°, 90°, 120°, 150°, 180°). Each child saw one of two randomized orders of questions. The randomization of question order was not related to the randomization into conditions. Children received no feedback on test items and there was no time limit.

After completing the main test items, children were presented with two questions from the mental rotation test, one 90° question and one 180° question. All the children were asked the same two questions. After reconfirming their answers, the children were then asked to record themselves explaining why they chose their answer. Thus, each child provided two strategy responses. Additional instructions

Table 1: Observed Mental Rotation Strategies (in %).

Strategy	Frequency Experiment 1	Frequency Experiment 2	Difference	Description of Strategy
Rotation	17.1	17.1	+0	Child described rotating stimuli.
Orientation	15.9	20.1	+4.2	Child described using the orientation or directionality of the answer choices.
Flipping	12.9	3.0	-9.9	Child described "flipping" the answer choices.
Feature Matching	11.8	9.8	-2	Child described focusing on non-orientation-based features.
Don't Know/ Guessing	7.6	4.9	-2.7	Child stated that they do not have a strategy.
General Mental Activity	6.5	2.4	-4.1	Child described using mental processes to determine the answer.
Unspecified Movement	4.7	1.2	-3.5	Child described imagining unspecified movement of the stimuli.
Analytic	2.4	7.3	+4.9	Child described using internal angles of the stimuli.
Perspective Taking	1.8	1.2	-0.6	Child described turning their own head.
Answer Location	0.6	1.8	+1.2	Child described consistently picking answer based on side of the screen.
No Answer	18.9	31.1	+12.2	Child did not answer or were unintelligible.

were given to parents to help children create the recording. While parents were instructed to encourage their child to answer and to restate the question if needed, parents were instructed to avoid leading their child to any particular answer. These strategy videos were then used to classify children's reported strategy use by two trained members of the research team. These individuals classified strategies independently, and inter-rater reliability was .82. When there was disagreement, the raters discussed until they reached consensus. Children were recorded during all parts of the study, to ensure that they completed the study without external help.

Results

Mental Rotation Performance Overall, mean performance on the mental rotation test was $M = 14.4$ ($SD = 2.77$), which is significantly above chance ($t(84) = 13.1$, $p < .001$). Age was significantly correlated with score ($r = .380$, $p = <.001$), but there was no significant difference between males ($M = 14$, $SD = 2.65$) and females ($M = 14.5$, $SD = 2.65$; $t(80) = 0.858$, $p < .393$). Children in the control condition ($M = 15.1$, $SD = 2.79$) performed better than children in the spatial language condition ($M = 13.8$, 2.61; $t(83) = 2.39$, $p = .019$). However, this effect of condition on score was not significant after controlling for age ($F(1,164) = 3.17$, $p = .077$.

Mental Rotation Strategies Out of all the strategy responses, 81.1% of children's strategy responses could be categorized. Responses that could not be classified included responses where the audio was unintelligible or the child did not address the question. Thus, instances where there was no response were left out of analyses. Strategies, their frequency, and examples are listed in Table 1. There was not a significant difference in strategy between the two conditions, $\chi^2(11, 170) = 10.2$, $p = 0.511$.

Discussion

In Experiment 1, children reported that they used several strategies other than rotation during the mental rotation test. Further, the specific strategies that children used on the present mental rotation test differed from results from previous studies that used a different mental rotation paradigm (Quaiser-Pohl et al., 2010). Of particular interest are the strategies that are incongruent with the task. For example, one of these new strategies, "flipping" the answer choices (See Table 1), will always result in the wrong answer. Since this flipping strategy has not been reported before, this strategy may be the result of the particular mental rotation paradigm used here. Our findings of these unique strategies suggest that the specific mental rotation test used could be a source of variability in children's strategy use.

Regarding strategy use in the spatial language and control conditions, the lack of difference could be because the language difference between conditions might have been too subtle to have an effect. If children were paying more attention to the visuals of the instructional video than the language used, then the language used in the instructions might not have mattered much in either condition. Thus, while our experimental conditions did not reveal strategy differences, we still captured variation in children's strategy use both within our experiment and compared to prior literature.

Additionally, there are strategies seen in previous research that were not present in our data. Specifically, children in the present study did not report using the gaze direction of the sea creatures to determine their answer or which sea creature was more “upright”. Although these strategies were used by children on a different test paradigm in prior research, they are not applicable with the current test. Thus, not having these strategies present in the current study provides some support that test design does influence strategy use.

Lastly, there is not a clear explanation for the control condition outperforming the spatial language on the mental rotation test, especially since there was not a significant difference in strategy between the conditions. However, it is possible that this difference in performance is not related to the instruction video differences, since there was no difference in strategy between the conditions.

Experiment 2

It is possible that the lack of difference between instruction conditions in the first experiment was due to the difference between conditions being too subtle, especially since children might have paid more attention to the visuals in the instruction video than the language used in the instruction video (Chabani & Hommel, 2014). To test this explanation, we conducted another experiment with more substantial changes to the instructions. Because we saw a unique set of strategies reported for our mental rotation test in Experiment 1, we designed a new instructional video targeting children who reported flipping the stimuli. We updated the instructions to encourage children to think about the stimuli in the test as stickers. We hypothesized that by introducing the test with this new context, children would be less likely to “flip” the stimuli, since stickers can only be placed down on one side.

Methods

Participants As in Experiment 1, children were recruited and participated online through LookIt (Scott & Schulz, 2017). A total of 104 new children between the ages of 4.5-to-6.5 years-old participated in this experiment. Some children were dropped from the analyses for not completing the study (*n* = 9), missing data due to technical error (*n* = 5), internet difficulties during study (*n* = 2), being outside of the age range (*n* = 1), not being typically developing (*n* = 3), and participating in the first experiment (*n* = 2). Thus, our total sample for Experiment 2 consisted of 82 children, with a mean age of M = 5.36 years (SD = 0.52, range 4.6 to 6.33, 41 females).

Design, Measures, and Procedure The procedures for Experiment 2 closely resembled those of Experiment 1. However, there was no randomization as all children were given the same sticker instructional video.

The instructional video used in this study was filmed instead of animated like in Experiment 1. The video showed a pair of hands from above with stickers that resembled the sea creature stimuli and a paper with a silhouette of a sea creature. Since this video was not animated, there was not a mermaid character that introduced the task. Instead, voice narration discussed the goal of the matching game and described how the hands in the video were rotating the stickers to see if they fit the silhouette. The language regarding rotation and the orientation of the sea creatures was the same as the spatial language condition in experiment 1. However, the context of stickers being used in the Experiment 2 version of the instruction also allowed for additional instruction about the sticky side of the sticker and how once a sticker was placed it could not be moved. The hands modeled rotating the stickers and matching them to the silhouette. The mental rotation test and practice questions were the same as in Experiment 1. Additionally, the strategy question procedure was the same as in Experiment 1. Inter-rater reliability for strategy classifications in Experiment 2 was 0.84.

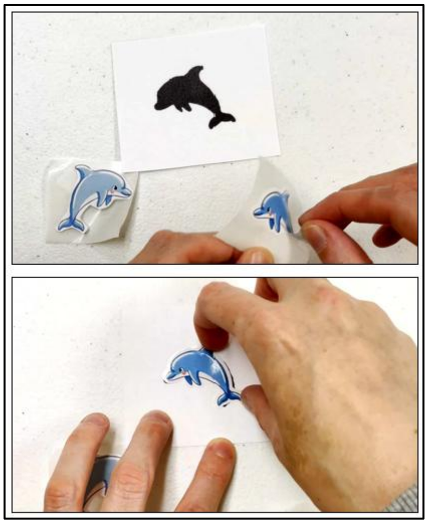

Figure 2. Examples from the
Sticker-Based Instructional Video

Results

Mental Rotation Performance Overall, mean performance of children in Experiment 2 on the mental rotation test was *M* = 13.4 (*SD* = 2.48), which is significantly above the chance level for the test ($t(82) = 10.8$, $p < .001$). As in Experiment 1, age was significantly, positively correlated with performance ($r = .284$, $p = .009$) and there was no significant difference between males (*M* = 13.7, *SD* = 2.69) and females (*M* = 13.1, *SD* = 2.16; $t(80) = 1.17$, $p = 0.246$).

Mental Rotation Strategies 68.5% of children’s strategy responses could be categorized. The strategies, their frequency, and examples are listed in Table 1. Overall, the strategy categories were the same as in Experiment 1. However, the frequency of strategies differed significantly between the two experiments ($\chi^2(11, 334) = 30.1$, $p = .002$). Specifically, the frequency of children reporting a flipping strategy decreased from 12.9% in Experiment 1 to 3.0% in

Experiment 2, which was a significant reduction ($t(332) = -3.35$, $p < .001$. Further, the frequency of orientation, analytic, and answer location strategies increased in Experiment 2, but only the increase in analytic strategies was significant ($t(332) = 2.13$, $p = .034$).

Discussion

The results from Experiment 2 suggest that children's mental rotation strategy use is malleable. By changing the instructions given before the mental rotation test, the frequency of reported strategies changed compared to Experiment 1. Specifically, we were able to target one erroneous strategy, flipping, and reduce it by creating a context for the test in which children could understand imagining the stimuli in 2D instead of 3D. However, the new instructions did not result in more children using rotation strategies.

Given the wide range of answers that children gave that were ultimately unclassifiable, it is not clear if there was a direct effect of the new instructional video on children's non-responses. If the instructional video did play a role, it is possible that children who would have otherwise used a flipping strategy no longer had a possible strategy and were less likely to answer the strategy question. However, it is also possible that the children in Experiment 2 were just less focused than children in Experiment 1.

General Discussion

This study aimed to explore children's mental rotation strategy use and how test design and instructions may affect these strategies. In Experiment 1, we observed a variety of strategies that children employed. Specifically, we found that some children used a flipping strategy, introducing a third dimension to the test, by reflecting the answer choices across a z-axis. This strategy has not been documented in previous literature on children's mental rotation strategies that used different tests (Estes, 1998; Quaiser-Pohl et al., 2010). In Experiment 2, we demonstrated the malleability of children's strategy use. By altering the instructions to include a "sticker" context, we were able to reduce the use of the "flipping" strategy. This reduction in flipping suggests that specific instructional cues can help guide children toward more appropriate strategies. However, despite the decrease in this erroneous strategy, we did not observe a corresponding increase in rotation-based strategies. While the sticker context seemed to provide a clearer framework for imagining the stimuli in 2D, it may not have been sufficient to shift children into using rotation strategies.

However, these findings illustrate the malleability of children's mental rotation. With further modifications to the instructional video accompanying our mental rotation test, it may be possible to create instructions that do increase the use of rotation. Spatial thinking has generally been recognized as malleable (Uttal et al., 2013). However, the malleability of spatial thinking is typically considered in terms of improvement through spatial training and interventions (e.g., Cheng & Mix, 2014). In this study, the malleability of children's strategies on a spatial test occurred during the administration of the test. Furthermore, the malleability described in this study may be more indicative of potential issues with the tests used rather than changes in children's spatial ability.

Our findings may call into question the validity of some mental rotation tests. In both of our experiments, children employed non-rotation strategies more often than rotation strategies. Thus, it may be inaccurate in some cases to describe mental rotation tests as measuring one's ability to mentally rotate a stimulus. It is possible that some of the children who used non-rotation strategies are capable of mental rotation but did not employ a rotation strategy during the test. Additionally, we must reconcile the validity of comparing test performance between children who use different strategies. To more validly measure mental rotation ability, researchers should consider how to limit alternative strategies. However, if mental rotation tests are considered a general measure of one's ability to solve a spatial problem, these alternative strategies may pose less of an issue for validity. For instance, children who did not use rotation but instead used an analytic strategy to arrive at the correct answer are still capable of solving the spatial problem presented in the mental rotation test.

Limitations

While the results of these two experiments highlight the importance of understanding children's strategy use, there are limitations of the present study design. First, these experiments used child self-report to determine strategy use. Despite previous research finding that young children are capable of describing their mental rotation strategies (Estes, 1998), children are also less likely than adults to give reliable descriptions of their mental processes. Other methods of determining an individual's strategy use during a mental rotation test, such as using eye-tracking or pupillometry may be more reliable than self-report, though are challenging with children (Campbell et al., 2018; Nazareth et al., 2019).

Further, other techniques that have been used to determine the reliability of strategy self-report, such as latent class analysis, do not work well with our mental rotation test due to the high chance level.

Second, this research was conducted entirely asynchronously online. While online research can allow for larger samples, the nature of this experiment meant that some families did not properly record their child's strategy response and there was no experimenter present that could try to ensure children answer or attempt to answer the strategy questions. Thus, our experiments may have a higher percentage of "no answer" strategy responses than if this study had been conducted in person. Since there was not an experimenter present when children watched the instructional videos, there was no way to ensure that children were paying attention to the instructions.

Future Research

Despite the limitations of the current study, our results can provide a starting point for further research on children's mental rotation strategies. First, future research should investigate children's strategy use for a variety of other mental rotation test paradigms, such as those that involve a same/different judgement. Further, the possibility that other test features, such as the kind of stimuli and the modality of the instructions, may also impact strategy use.

Second, future research can use within-subject and longitudinal study designs to better understand the mechanisms of change behind the differences in strategy use. While the between-subjects design used in the present study provides a starting point for understanding how instructions may affect children's strategy use, digging deeper into possible change within individual children will give more insight into how external factors may influence children's strategies.

Lastly, there are many implications of the present research for existing spatial cognition literature. Because mental rotation is the most commonly used spatial test, many findings in spatial cognition research have relied on mental rotation tests. For example, many studies that have looked at the relationship between spatial cognition and STEM have relied on mental rotation. Therefore, mental rotation has been found to be highly correlated with STEM ability in children (e.g. Bruce & Hawes, 2014; Stieff, 2007). However, much of this research has not considered how children's strategy use may affect the relationship between mental rotation and STEM. For example, is mental rotation still correlated with math when children do not use a rotation strategy? Future research should consider strategy use when investigating the relationship between mental rotation test performance and other variables of interest.

Conclusion

Although our findings offer important insights into the development of mental rotation strategy use in children, our results also raise important questions about the validity of mental rotation tests themselves. If children are using primarily non-rotation strategies, we must reconsider how these tests are interpreted. For example, researchers should investigate if young children actual are unable to perform mental rotation or if they just do not understand what mental rotation tests are asking of them. Further, researchers should evaluate children's mental rotation tests that they use or design to determine the potential effects of the test on children's performance and strategy use.

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