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Using Manual Rotation and Gesture to Improve Mental Rotation in Preschoolers

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Abstract

We report the effects on accuracy and reaction time at a mental rotation task for four year old subjects who were either given practice rotating objects on a computer screen by turning a joystick or gesturing about rotating objects on a computer screen. We found that training children to gesture about rotation improves performance on MR. Children who were given practice rotating objects with a joystick do not show the same level of RT improvement as children who either gestured about movement or who simply practiced the task over the course of the experiment without any training.

Keywords: mental rotation, gesture, embodied cognition, preschoolers.

Introduction

In a typical Mental Rotation (MR) task, a subject is shown two stimuli, a comparison stimulus and a rotated stimulus, and is asked to respond as quickly and as accurately as possible as to whether the two stimuli are rotational variants or not. Reaction Time (RT) data from such studies show that subjects are increasingly slow to respond correctly as the level of angular disparity between the rotated stimulus and the comparison stimulus increases (e.g., Shepard & Metzler, 1971). This data pattern suggests that subjects are actively constructing mental representations of the stimuli and are executing mental emulations of physical rotation. One other common finding involving mental rotation is that men outperform women on a variety of mental rotation tasks (e.g., see Linn & Petersen, 1985 for a classic meta-analysis). A more recent study replicating this finding also found that men use a strategy involving actually mentally rotating stimuli, whereas women have a tendency to use analytic strategies that do not involve physical rotation (Geiser, Lehmann, & Eid, 2006). In other words, men tended to be "rotators" who used a strategy of mentally rotating objects to solve spatial problems, whereas women tended to be "non-rotators" who used feature matching or other strategies not reliant on mental transformation of the objects. There are also individual differences in MR ability, regardless of gender.

These gender and individual differences are important, given the relation of spatial skills such as mental rotation to success in STEM (science, technology, engineering and math) disciplines. Spatial skills predict STEM interest and achievement as well as entry into STEM careers, even after controlling for verbal and mathematical skills, (e.g., Wai, Lubinski, & Benbow, 2009).

A recent meta-analysis investigating whether spatial skills such as MR are malleable revealed that spatial skills can be trained, and that positive results of training can last over time and can be transferred to both near and far tasks (Uttal, et al., under review). Further, the meta-analysis showed that training leads to the greatest effect sizes when participants are children under age 13. Relative to research in training MR in adults, the benefits of training children have been less clearly defined. However, identifying the methods that lead to improved spatial skills particularly in young children is necessary in order to make greater strides in bridging gender and socioeconomic gaps that are present at very early ages.

Differences in MR skills are evident early on. Levine and colleagues (1999) found that even among preschoolers, boys performed more accurately than girls on a two-dimensional spatial task requiring mental rotation and/or translation. In a more recent study, Levine et al. (2005) reported that sex differences on spatial tasks in elementary school children varied as a function of socioeconomic status (SES). In higher- and middle- SES groups, the study replicated the common sex difference finding: boys performed more accurately than girls. However, in the lower-SES group, boys and girls performed equally (and more poorly than the other children) on the spatial tasks. The authors suggest that lower-SES families may have less access to spatially relevant toys and activities and thus neither boys nor girls have well developed spatial skills. In contrast, higher- and middle- SES families do have access to such stimulation. However, boys are more likely than girls to engage in spatial activities (e.g., play that promotes the development of spatial skill such as block building and playing video games). The fact that the sex difference was present in only certain groups of children suggests that engaging in spatial activities during childhood might contribute to the commonly reported male advantage for MR.

One such spatial activity is computer game play. Training studies that incorporate computer games have been found to improve mental rotation skills across gender and age groups. Both women and men showed improved mental rotation skills following longitudinal spatial computer game play that involved rotating two-dimensional blocks to fit within a pattern (Terlecki, Newcombe, & Little, 2008). Computer game training using a spatial game of weights and pulleys eliminated sex differences altogether in adolescents (McClurg & Chaille, 1987). Thus, computer games offer a unique opportunity for investigating spatial training methods since they are effective at increasing spatial skills among both males and females, they are increasingly becoming more available to a range of SES groups, and they are a popular source of entertainment among children.

In many video games, an individual manipulates their field of view or an object on the screen, often through rotating a joystick. Moulton and Kosslyn (2009) have argued that MR is an instance of mental emulation—a process that involves activation of visual and motor systems that overlap with cognitive resources that would be used to actually manipulate 3D objects. In fact, a number of studies have shown that movement can interfere with MR. For example, Wexler, Kosslyn, and Berthoz (1998) demonstrated that the speed of mental rotation is affected by the direction, angle and speed at which participants rotate their hands while doing an MR task. This suggests that perhaps training subjects to move in certain ways could have positive effects on MR performance. In fact, training involving using a joystick to rotate two-dimensional figures increased MR performance and eliminated sex differences in adolescents (Weidenbauer & Jansen-Osmann, 2007). Training effects observed by Weidenbauer and colleagues extended to a somewhat broader range of contexts than only those experienced during training.

Hand gestures, a specific type of movement, have also been studied with respect to MR. Analyses of people's spontaneous production indicates that people tend to gesture when talking about MR tasks (Chu & Kita, 2008). Further, 5 year old children perform better on a simple two-dimensional MR task if they gesture about movement during their explanations than if they do not, and boys are more likely to gesture about movement during an MR task than are girls (Ehrlich et al., 2006). Gesturing not only reflects a young child's knowledge of the MR task, but it can also play a role in changing that knowledge. Recent findings suggest that children who were told to produce gestures that mimicked physical rotation were more likely to profit from instruction on a 2-D MR task than children who were told to point at the objects that needed to be mentally rotated (Zinchenko, et al., 2010). What remains to be seen is whether gesture (representational movement) and joystick rotation (actual movement) are equally useful in improving children's MR performance.

Thus, the current study examines these two possible training methods. One group of children (rotation training condition) used a joystick to rotate a rotated animal picture to face right-side-up next to a comparison animal picture. Another group of children (gesture training condition) were instructed to gesture how they would rotate the rotated animal picture to face right-side-up next to the comparison animal picture. These two types of training allowed us to investigate how MR training impacts young children using either transitive action (e.g., manually rotating a joystick) or more abstract representational action (e.g, gesture the movement needed to match the orientation of a rotated animal picture into right-side-up alignment with another). We hypothesized that engaging in rotation movement, either manual rotation or gesturing rotation, would improve spatial performance, whereas engaging in a verbally focused computer task (no training condition) would not elicit spatial improvement to the same degree. The question of interest here involves the relative effectiveness of actual rotation vs. gesture. On one hand, children in the rotation condition receive visual feedback during training—they could see the object rotating as well as the outcome of having rotated the object. On the other hand, children in the gesture condition might visualize the rotation (as well as having the positive benefit of engaging the motor system), as they cannot see the objects move. To address whether actually moving the objects or gesturing the movement is more beneficial to mental rotation skill, we compared pre- to posttest performance for the two groups on the trained task as well as well as on a transfer task, as well as reaction time on the trained task.

Method

Participants

Sixty-three four-year-old children participated in this study. Participants were recruited from Chicago and nearby suburbs. Participants were randomly assigned to either the rotation training condition (N=20, 11 girls; M=4.49 years, SD=0.36 years), the gesture training condition (N=22, 10 girls; M=4.59 years, SD=0.49 years) or the no training condition (N=21, 11 female; M=4.50 years SD=0.38 years).

Design and Procedure

The experiment followed a pretest-training-posttest paradigm. Children were randomly assigned to one of three training conditions, described in detail below. Children completed some of the activities on a PC with a 17" monitor. Input devices included a two-button child-friendly mouse and a sidewinder precision joystick.

Pretest During the pretest, all children first completed the Child Mental Transformation Task (CMTT; the transfer task in this particular experiment), then the Mental Rotation Task (MROT; the trained task in this particular experiment).

All children first completed 12 trials of the CMTT (Levine, et al., 1999). The task presents a child with two halves of a 2-D shape that has been cut by its vertical line of symmetry. The two halves are rotated and/or translated apart from one another. Children are shown four possible target shapes and are asked which shape would be made if the two halves were put together. This task is often used to study MR and spatial visualization skills and strategies in preschool children. In the current study, we did not train children using the CMTT; it serves as a transfer task measure.

Children then moved onto the pretest section of the trained task. The Mental Rotation Task, or MROT, requires children to decide as quickly and accurately as possible whether two animals, presented side by side on a PC screen, are walking in the same direction (once they're both on their feet). The picture on the left (comparison picture) is on its feet and facing either right or left. The picture on the right (rotated picture) is presented in one of four angular disparities relative to the comparison picture. The rotated picture (when turned to be on its feet) was identical for the 12 'same' trials and was mirror-reversed for the 12 'different' trials. Children were asked to answer "same" if the (rotated) animal on the right side of the screen would be walking in the same direction or in a different direction than the (comparison) animal on the left side of the screen (already on its feet). 12 practice trials were administered to ensure understanding of the task, and children received feedback. Following these trials, 24 pretest trials were administered with no feedback. On each test trial, two images of the same animal (either an elephant, fox, alligator, cow, leopard, or horse) were presented simultaneously. Each trial started with a presentation of a grey fixation square followed by the two drawings and a prompt for the child to respond by pressing a "same" or "different" button.

On the first trial, the experimenter pointed to the pictures on the screen and said, "This game shows two animals on the screen. One of them is turned, and you have to decide whether the two animals are going the same direction or different directions. This one (pointing to the rotated animal on the right) isn't on its feet. If we turned it on its feet, does it look the same as this one (pointing to the comparison animal on the right)? Are they going the same direction or different directions? Try to pick the answer as fast as you can." The children were asked to click the left (blue) button on the mouse if both animals were heading in the same direction or the right (red) button on the mouse if the animals were heading in different directions.

Training Each subject was randomly assigned to one of three training conditions: rotation training condition, gesture training condition, or no training condition.

In the rotation training condition, the experimenter introduced the training phase by saying, "This time the animals are always facing the same direction, but one of them is turned around and not on its feet. Help the animal that is turned around to get right-side-up and on its feet by rotating the joystick until the animal matches the one on its feet. See, if you turn the stick to the right, the animal moves that way, and if you turn the stick to the left, the animal moves that way. Make sure you turn the animal so that both of them look exactly the same. Try to match them up as fast as you can." Using a joystick to manipulate the stimuli, children were instructed to click the center (green) button on the joystick when they felt the two animals matched. 36 trials, 12 with correct/incorrect feedback presented immediately after the green button was clicked, followed by 24 without correct/incorrect feedback, were administered. In the rotation training condition, the animal picture on the right actually moved in response to the child's joystick rotation.

In the gesture training condition, the experimenter introduced the training phase by saying, "This time the animals are always facing the same direction, but one of them is turned around and not on its feet. Help the animal that is turned around to get right-side-up and on its feet by using your hand to rotate him around so the animal matches the first one on its feet, like this (experimenter demonstrated a grabbing and rotating gesture near the animal)." Children were instructed to touch their hand to the screen and show how they would rotate the animal to move it on its feet. 36 trials, 12 with incorrect/correct feedback followed by 24 without feedback, were administered. In the gesture training condition, the rotated animal picture on the right did not actually move during training.

An unrelated game was used as a filler task for children in the no training condition. In one trial of this activity, a letter falls from the top of the screen to the bottom of the screen. The task requires the child to select and click the letter that follows the falling letter on a child-size keyboard before the letter hits the bottom of the screen. The program ran for 10 minutes (the approximate time of the rotation and gesture training conditions).

Posttest At posttest, all children completed 48 trials of the MROT with novel animal stimuli that had not been seen at pretest or during training (bear; donkey; dog; pig; tiger; goat; camel; lion; rhinoceros; deer; sheep; raccoon). Children were first reminded of the directions and then were asked to complete the task as quickly and accurately as possible. Following the MROT (trained task), children completed 12 novel trials of the CMTT (transfer task).

Results

Accuracy on Trained Task (MROT)

Raw accuracy data for the MROT at pretest and at posttest are presented in Table 1. Since previous studies have found that simply practicing mental rotation improves performance (see Baenninger & Newcombe, 1989), we predicted that all subjects would improve from pretest to posttest. Average accuracy on the MROT at pretest was 66.07% (SE=2.25%); accuracy at posttest was 71.92% (SE=2.26%), a significantly higher score ($t(62)=3.31$, $p<0.01$). All subjects became more accurate at the MROT from pretest to posttest, regardless of condition.

To investigate the *relative* improvement from pretest to posttest by condition, we first calculated 4 change scores (one for each angular disparity) for each subject by extracting standardized residuals from a linear model predicting posttest accuracy from pretest accuracy. These change scores represent each subject's improvement from pretest to posttest relative to all other subjects (similar to a z-score), accounting for accuracy at pretest. As such, they provide information about the benefit of each training condition relative the others. We entered these change scores into a repeated-measures ANOVA with Condition (3:

rotation training, gesture training, no training) and Sex (2: male, female) as between subjects variables and Angular Disparity (4: 157.5, 122.5, 67.5, 22.5) as a within subjects variable. Age was entered as a covariate.

Table 1: MROT accuracy, percent correct (SEM).

			Angular Disparity (in degrees)			
			157.5	122.5	67.5	22.5
Rotation training	Boys	Pre	46 (11)	56 (9)	71 (9)	67 (9)
		Post	67 (7)	67 (6)	74 (7)	79 (7)
	Girls	Pre	47 (7)	56 (7)	66 (9)	74 (8)
		Post	42 (6)	54 (5)	68 (5)	77 (5)
Gesture training	Boys	Pre	61 (10)	76 (6)	82 (6)	88 (5)
		Post	74 (5)	76 (5)	86 (5)	92 (6)
	Girls	Pre	41 (10)	71 (8)	72 (9)	82 (8)
		Post	59 (9)	77 (7)	83 (6)	90 (5)
No training	Boys	Pre	58 (7)	75 (9)	70 (11)	84 (9)
		Post	63 (5)	71 (4)	79 (4)	83 (5)
	Girls	Pre	43 (8)	58 (7)	76 (7)	73 (7)
		Post	53 (4)	65 (4)	77 (3)	81 (4)

We found a main effect of Condition on change scores, *F*(2, 56)=3.85, *p*<0.05. Planned contrasts using the Bonferroni correction showed that, relative to subjects in the no training condition (M=-0.28, SE=0.15), subjects in the gesture training condition (M=0.30, SE=0.15) improved more from pre to posttest. Rotation training condition change scores (M=-0.04, SE=0.15) did not significantly differ from either of the other conditions, and are intermediate in terms of the other two conditions. Since everyone improved from pretest to posttest, subjects in the rotation training condition, who had scores close to zero, can be thought of as "average improvers". Similar to z-scores, a change score of zero represents average improvement. In contrast, subjects in the no training condition improved least, and subjects in the gesture training condition improved most. This difference between gesture and no training conditions was significant. These findings all controlled for age, and no other main effects or interactions in the ANOVA were significant.

Reaction Time on Trained Task (MROT)

Reaction Times (RTs) were analyzed only for trials where subjects responded correctly. We also removed outliers for each subject, by only including RTs within 2 standard deviations of each subjects' mean, figured separately for pretest and for posttest. Raw RT data (for trials meeting these criteria) for the MROT at pretest and at posttest are presented in Table 3. Log-transformed RT scores (calculated in the service of normalizing skewed RT data) are used in all analyses and subsequent calculations presented in this section.

Table 2: MROT RT (ms) at pretest (SEM).

			Angular Disparity (in degrees)			
			157.5	122.5	67.5	22.5
Rotation training	Boys	Pre	6592 (1646)	4264 (1106)	5615 (1489)	4732 (1026)
		Post	2877 (484)	3451 (582)	2668 (509)	3084 (591)
	Girls	Pre	7474 (2230)	6281 (1673)	5558 (1088)	5727 (1114)
		Post	4789 (889)	5586 (879)	5171 (881)	5012 (850)
Gesture training	Boys	Pre	4655 (776)	4350 (563)	4405 (688)	3965 (549)
		Post	3262 (625)	2898 (516)	2982 (601)	2562 (399)
	Girls	Pre	7129 (1042)	6807 (1152)	6446 (1011)	5699 (945)
		Post	2182 (474)	1995 (296)	1849 (296)	1789 (326)
No training	Boys	Pre	7543 (1696)	6883 (1167)	6589 (1113)	5357 (790)
		Post	2453 (737)	2858 (728)	2326 (592)	2151 (572)
	Girls	Pre	4330 (691)	3974 (978)	3056 (628)	3140 (304)
		Post	2617 (294)	2217 (258)	2383 (298)	2242 (2330

We predicted an overall practice-effect type of increase in reaction time on the MROT from pretest to posttest. Overall average RT at pretest was 5256 ms (SE=389 ms) (logRT: M=3.65, SE=0.03); overall average RT at posttest was 3022 ms (SE=257 ms) (logRT: M=3.38, SE=0.04). Overall, logRT (and thus RT[1]) decreased with practice on the task (*t*(62)=6.43, *p*<0.001).

To investigate the relative improvement from pretest to posttest by training condition, we calculated 4 change scores (one for each angular disparity) for each subject by extracting standardized residuals from a linear model predicting posttest RT from pretest RT[2]. As with the accuracy change scores reported above, RT change scores represent each subject's improvement over time relative to all other subjects (like a z-score), and also account for accuracy at pretest. With RT, though, negative change

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[1] Analyses using raw RTs found the same pattern of results.

[2] LogRTs were used in the actual calcuations.

scores represent relatively greater speed improvement while positive change scores represent relatively less speed improvement. As with accuracy, we entered these RT change scores into a repeated-measures ANOVA, with Condition (3: rotation, gesture, control) and Sex (2: male, female) as between subjects variables, and Angular Disparity (4: 157.5, 122.5, 67.5, 22.5) as a within subjects variable. Age was entered as a covariate. The Greenhouse-Geisser correction was used to account for non-sphericity of the change score data[3].

We found a main effect of Condition, $F(2, 49)=3.80$, $p<0.05$. Planned contrasts using the Bonferroni correction revealed a significant difference between change scores for chidren in the gesture training condition (M=-0.28, SE=0.19) and change scores for subjects in the rotation training condition (M=0.44, SE=0.21). There was a marginally significant difference ($p<0.08$) between the rotation condition and the no training condition (M=-0.22, SE=0.19), and no difference between the gesture and control conditions. Recall that, with RTs, negative change scores represent relatively greater speed improvement. Though all participants got faster from pretest to posttest, RTs of those who practiced actually rotating objects during training improved least from pre to posttest. In contrast, either gesturing about the physical rotation of objects during training or completing an unrelated control task resulted in relatively greater speed improvement from pretest to posttest.

However, this finding is qualified by a significant Sex x Condition interaction, $F(2, 49)=5.52$, $p<0.01$. ANOVAs including Condition and Angular Disparity and controlling for Age were calculated, separately for boys and for girls. The ANOVA for boys did not reveal any significant main effects or interactions (no training M=-0.57, SE=0.31; gesture M=0.23, SE=0.28; rotation M=0.11, SE=0.37, all ps>0.30). In other words, boys got faster on the MROT from pretest to posttest, but none of the training conditions showed any significant benefit over the other with respect to RT. This suggests a pure practice effect for boys' speed in MR. In contrast, the ANOVA for girls showed a significant main effect of Condition, $F(2, 26)=10.15$, $p<0.001$. Girls in the no training condition had average change scores of exactly 0.00 (SE=0.25). The speed of girls who were in the no training condition (and so simply practiced MR over the course of the experiment) improved; this represents a baseline for girls' speed improvement. RTs of girls in the rotation training condition showed a trend toward being significantly higher (indicating relatively less improvement in the case of RT; M=0.82, SE=0.23; $p<0.08$) than girls in the no training condition. There was not a significant difference between gesture training condition change scores (M=-0.73, SE=0.26) and no training condition change scores ($p>0.15$). However, there was a significant difference between the gesture and rotation training conditions ($p<0.001$). This result indicates that, for girls, gesturing about rotation, compared to practice physically rotating objects with a joystick, results in increased speed for performing the mental rotation task (MROT). These findings suggest that girls in the rotation training condition may have become somewhat dependent on seeing the outcome of rotating objects during training. Conversely, gesturing about rotation may be particularly apt for helping girls to visualize the outcome of rotations, resulting in a rather large relative improvement in RT on the trained mental rotation task.

Accuracy on Transfer Task (CMTT)

Raw accuracy data for the CMTT at pretest and at posttest are presented in Table 3. We first asked whether practicing MR during the MROT (in pretest and posttest for all participants, and also in training for subjects in the rotation and gesture training conditions) increased accuracy on the CMTT. The CMTT focuses on MR, but is 2-D and presented on paper instead of on a computer screen. It also uses black outlines of shapes instead of realistic stimuli like pictures of animals, and sometimes calls for spatial translation instead of or in concert with rotation. As such, it is a near transfer task. At pretest, across all subjects, accuracy on the CMTT task was 40.61% (SE=2.04%); accuracy at posttest was 50.66% (SE=2.92). This improvement was significant, $t(62)=4.23$, $p<0.001$.

Table 3: CMTT accuracy (percent correct) at pretest and at posttest (SEM).

		Pretest	Posttest
Rotation training	Boys	38 (5)	54 (7)
	Girls	42 (4)	55 (8)
Gesture training	Boys	44 (6)	65 (5)
	Girls	38 (4)	53 (8)
No training	Boys	40 (6)	40 (7)
	Girls	39 (5)	36 (4)

To see how the training conditions differentially affected accuracy on the CMTT, we calculated change scores for each subject by extracting standardized residuals from a linear model predicting posttest CMTT accuracy from pretest CMTT accuracy. Greater change scores represent relatively greater improvement on the transfer task from pretest to posttest. Change scores were entered into an ANOVA with Condition (3: gesture, rotation, control) and Sex (2: male, female) as between subjects variables and Age as a covariate. The ANOVA only revealed a main effect of Condition, $F(2, 56)=8.18$, $p<0.001$. Change scores for subjects in the rotation condition (M=0.20, SE=0.20) and for subjects in the gesture condition (M=0.43, SE=0.20) were significantly better than change scores for subjects in the no training condition (M=-0.64, SE=0.20). Change scores for the gesture and rotation conditions were not significantly different from one another. In other words, the additional practice on the MROT that subjects in the gesture and rotation training conditions received improved their

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[3] RT data was non-spherical in general, at pretest and at posttest.

scores on the transfer task, relative to completing an unrelated control task during that time.

Discussion

In terms of accuracy on a MR task, children who got practice gesturing about rotating objects improved most from pretest to posttest, compared to children who participated in an unrelated task during the training session. Children who had practice actually rotating objects showed average improvement compared to the other conditions. Interestingly, children in both of the gesture training and no training conditions got faster at MR from pretest to posttest, while RT for children in the rotation training condition did not improve as much from pretest to posttest. This pattern of findings suggests that a) training children to gesture about rotation improves performance on MR; b) giving children practice physically rotating objects may lead them to become somewhat dependent on this physical rotation—these children do not show the same level of RT improvement as children who either gestured about movement or who simply practiced MR over the course of the experiment. In terms of transfer, children who participated in either training condition showed relatively greater improvement on a non-computer MR task than did children who did not receive any training. In this case, it is difficult to say whether the training conditions had any benefit besides exposing children to more practice on the task. In this study, we did not find any effects of angular disparity on learning—subjects improved equally for rotations at each of the four angular disparities. With one exception, discussed below, we did not find sex differences as far as training benefits.

In our study, girls were especially likely to show faster RTs when they were given practice gesturing about rotation. Previous studies have shown that boys are naturally more likely to gesture about rotation and also that spontaneously gesturing about the rotating objects is positively associated with performance on an MR task (Ehrlich et al., 2006). This suggests that encouraging (particularly girls) to embody concepts of rotation and to express those concepts by gesturing improves their MR performance.

Future research could address whether gesture vs. rotation training transfers to tasks that are farther from MR, but still related. Future research could also investigate how long the positive effects of training last. Lastly, studies could be conducted that delineate the mechanisms behind gesture and manual rotation in improving mental rotation and other spatial skills.

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