Effects of Collaborative Spatial Exercises on the Acquisition of Mental Rotation Ability

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Abstract

This study aims to determine whether commercially available games claiming to expand spatial awareness actually increase understanding of mental rotation and whether collaborative learning techniques are beneficial to the learning of mental rotation in this context. To test these questions, 40 children from the CMU Children's School were randomly assigned to work individually or collaboratively to complete either building block replication tasks or mental rotation block challenges. Four and five-year-old children participated in three training sessions, flanked by a pretest and posttest using the Children's Mental Transformation Task. Results showed a significant increase in mental rotation ability overall, but the difference between groups was not significant. These results suggest that while the commercially-available mental rotation games do improve mental rotation ability, they are not significantly more effective than building replication tasks that pose fewer overt mental rotation demands. Additionally, individuals working collaboratively did not demonstrate greater improvement in mental rotation.

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Over the past few decades, researchers in the field of child development have become increasingly interested in collaboration (Johnson, Skon, & Johnson, 1980; Fawcett & Garton, 2005; Butler & Walton, 2013). Collaboration is fundamental to human functioning, demonstrated as early as infancy, when children point to obtain an object that they are unable to reach themselves, through adulthood, when individuals form teams to solve difficult problems. Given that collaboration is such an inherent part of human experience, it is important that we understand what collaboration is and under what circumstances it is effective so that we can use collaborative learning techniques to our advantage in learning and teaching. Particularly, application of collaborative learning techniques to the acquisition of spatial understanding has been neglected by current research. As spatial awareness skills have been shown to predict success in fields of science and engineering (Newcombe 2010), working collaboratively to gain this understanding at an earlier age may be beneficial to children's future success.

As defined by the Merriam-Webster dictionary, collaboration occurs when an individual "work[s] with another person or group in order to achieve or do something" (Collaboration, n.d.). Bratman (1992) describes a very similar concept in his review of "shared cooperative activity," which he describes as engagement in any activity by at least two people who demonstrate mutual responsiveness, commitment to the joint activity, and commitment to mutual support. Importantly, collaborative efforts produce a joint product or achieve a joint goal. The results of collaboration are understood to represent the shared conclusions of the group (Roschelle & Teasley, 1995). What is perhaps most interesting to researchers is to understand the characteristics that correlate with successful achievement of goals through collaboration.

According to Murphy and Faulkner (2000), effective collaboration can be achieved through strategies such as reminding partners of a rule, asking questions, justifying disagreement through explanations of one's thought processes, and gazing at one's partner. Ineffective collaboration tends to be marked by disagreement with little attempt to explain one's understanding, violations of rules, and negative facial expressions.

Historically, views of learning efficacy have been divided between two competing theories: Piagetian theory and sociocultural theory. Piagetian theory, established by Jean Piaget, follows what is referred to as an "inside-out" approach to learning (Garton 2004). By this framework, children gain knowledge when their understanding is at a state of disequilibrium with their experiences with the physical world. Piaget asserted that "as a higher level of understanding emerged, through dialogue and discussion among individuals of equal status, equilibration was restored and, simultaneously, cognitive change occurred," (Fawcett & Garton 2005). Thus, learning from Piaget's point of view is an internal process that subsequently manifests itself in a child's outward behavior. Lev Vygotsky's sociocultural theory of learning (Vygotsky 1997), on the other hand, has offered an "outside-in" (Garton 2004) explanation as to how collaboration aids in the learning of novel concepts. Vygotsky proposed the notion of a zone of proximal development, which refers to the tasks that are feasibly achievable by a child with the support of another more knowledgeable individual. Additionally, Vygotsky theorized that intersubjectivity, or the "process whereby two participants in a task who begin with different understandings arrive at a shared understanding in the course of communication" (Tudge 1992), is a driving force behind the process of collaborative learning. Simply put, Vygotsky asserted that individuals must be of differing levels of understanding for a cognitive change to occur through collaboration.

Researchers have accrued a large body of evidence regarding the effectiveness of collaborative learning techniques employed by young children. In a study conducted by Johnson, Skon, and Johnson (1980), first graders were assigned to work in either cooperative pairs, competitive pairs, or individually on three separate tasks: a categorization/retrieval task, a spatial reasoning task, and a verbal problem-solving task. The researchers discovered that children in the cooperative condition significantly outperformed children in the competitive condition on both the verbal problem-solving and categorization/retrieval tasks and outperformed the children who worked individually on all three tasks. These results demonstrate that collaboration and cooperation can be beneficial to performance on academic tasks, even at a young age.

Phelps & Damon (1989) suggested that collaborative learning is not, however, beneficial when utilized to improve performance on tasks involving rote memorization, but that it can be a successful technique when used to improve tasks that involve reasoning. Spatial awareness is one of many cognitive reasoning skills that is largely undeveloped in very early childhood, and thus I hypothesize that development of spatial awareness may be advanced by collaborative learning techniques. Spatial analysis is defined by Stiles & Stern (2001) as “the ability to specify both the overall configuration of a visually presented pattern and to understand how the parts are related to form a whole,” (p. 158). This ability often manifests itself in young children’s play with building blocks. In a 1988 study on children’s block building behaviors, Stiles-Davis noted that children rarely construct block buildings in more than a single dimension until approximately 4 years of age. This development of dimensionality in building is evidence that children are acquiring a greater understanding of spatial relationships, as they arrange objects within a three-dimensional space.

The present study will focus on mental rotation ability, one of the skill components within spatial awareness. Mental rotation ability refers to “the imagined movement of an object (or array of objects) in 2- or 3-dimensional space” (Frick, Ferrara, & Newcombe 2013). Though mental rotation has largely been studied in adults, numerous studies have led to the belief that mental rotation skills may develop as early as four years of age, with significant progress occurring between ages 4 and 5. One such study involved presenting 3.5 to 5.5 year olds with pairs of two cardboard shapes, one that would and one that would not fit into a provided hole (Frick, Ferrara, & Newcombe 2013). Children were assigned to receive manual experience (where they were allowed to rotate and move the cardboard piece to determine fit), observation (where children only observed an adult move the selected piece to determine fit), or no experience. Researchers determined that 5-year-olds demonstrated a statistically significant reduction in error rate when compared to 4-year-olds and that 5-year-olds achieved increased response accuracy after both the manual experience and observation conditions. Additionally, error rate for 5-year-olds increased linearly as the angle of the piece’s presentation increased (i.e., less rotation of the piece at initial presentation was associated with a lower error rate), while 4-year-olds maintained a steady error rate regardless of rotation angle. This finding suggests that younger children were not applying mental rotation strategies and that children around five years of age exhibit a readiness to employ mental rotation strategies. Similar results were found by Estes (1998) who presented 4-year-olds, 6-year-olds, and adults with image pairs of monkeys who were either raising the same arm or opposite arms. The monkey on the right-hand side was presented at various angles and participants were asked to determine whether the monkeys were raising the same arm. While only 3 out of 20 four-year-olds explained their answers with reference to mental rotation, 15 out of 20 six-year-olds did, indicating an increase in awareness of mental rotation between these ages. Additionally, children who explained their answers using mental rotation did, in fact, perform better on the task, demonstrating an error rate consistent with the use of mental rotation strategies (Estes 1998). Consequently, not only can children demonstrate use of these strategies at an earlier age than was initially believed, but some are even able to identify and verbalize this mental strategy. Interestingly, the ability to recognize one's use of mental rotation and verbalize this strategy was associated with improved performance on mental rotation tasks. Additionally, males tend to perform better on mental rotation tasks. Evidence for this finding has been mixed at younger age ranges, but a difference has been noted as early as 4.5 years of age (Erlich, Levine, & Goldin-Meadow 2006).

The present study aims to integrate the literature on mental rotation ability and research on collaborative learning techniques. At this point, there has been a lack of research regarding whether or not spatial exercises can accelerate young children's acquisition of mental rotation ability and if it does, whether or not collaboration would improve the efficacy of these exercises. It is possible that a better understanding of the interaction between collaborative learning techniques and the effects of practice performing spatial tasks will allow for the development of teaching techniques to improve spatial understanding in young children. Teachers would then be in a position to help increase this cognitive ability at an accelerated rate, which would help students attain higher scores on many achievement tests and achieve early success in science, technology, engineering, and math fields (Newcombe 2010).

This study examined whether or not children acquire improved mental rotation ability from commercially marketed spatial building block challenges and whether or not completing these challenges collaboratively enhances the progress in mental rotation ability. Training sessions required playing either three separate sets of commercial spatial awareness building block challenges or three different sets of building replication tasks, designed to require similar pattern matching without a need for mental rotation. Mental rotation ability progress was assessed before and after the spatial exercises using the Children's Mental Transformation Task, or CMTT (Levine, Huttenlocher, Taylor, & Langrock 1999). The task involves mentally manipulating two shapes in order to produce one of four answer options for their combined shape. The two initial shapes are presented at varying degrees of rotation from their position in the target shape, necessitating the use of mental rotation to choose the correct response.

Based on the prior literature, I predicted that participation in spatial building block challenges would in fact cause children to significantly improve their performance on the CMTT, thus illustrating an increase in mental rotation skill. Additionally, I hypothesize that the improvement demonstrated by children who completed the spatial building block challenges will be significantly greater than any gains in CMTT score achieved by children who completed only the building replication tasks, as these tasks do not require them to practice mental rotation skills. I hypothesize that collaboration on these tasks will be correlated with an increase in CMTT performance, given the evidence that collaborative learning techniques often increase an individual's performance on reasoning tasks. Lastly, I hypothesize that males will perform better on the CMTT and both spatial tasks than will females, given the existing research that demonstrates that males typically perform better than females on spatially-related tasks (Levine, Huttenlocher, Taylor, & Langrock 1999).

Method

Participants

A total of 40 children participated in the present study (mean age = 5.03, *SD* = 0.45, 24 females and 16 males). All participants were recruited through the Carnegie Mellon University

Children's School in Pittsburgh, Pennsylvania. The Children's School is a laboratory school associated with Carnegie Mellon University. Parents read and sign a consent form at the beginning of the academic year that provides consent for their children to participate in all studies conducted by CMU researchers at the school, so long as the studies have been approved by the Institutional Review Board (IRB). The IRB approval letter for the present study can be found in Appendix A. Additionally, this study complied with all Children's School research procedures, including providing parents with a description of the study following their child's participation (see Appendix B). Each research session took no longer than twenty minutes, the maximum time allowed by Children's School policies, and children only participated in one experiment per day.

Each child was randomly assigned to one work either individually or collaboratively on Mental Rotation challenges or Building Replication challenges. Children in the collaborative conditions were paired based on class (4-year-old and Kindergarten) and gender, as previous research has examined collaborative learning primarily with same-gendered pairs (e.g., Phelps & Damon 1989; Murphy & Faulkner 2000). Additionally, one pair was eliminated from the study after the pretest as a result of behavioral issues. The experimenter and educators agreed that the two children would likely be unable to work collaboratively to complete the tasks.

Because a cohort model was used for the duration of the experiment, children were not matched by level of initial mental rotation ability as determined by the CMTT. To do so would have required an initial pretesting of all children, significantly increasing the length of time between pretest and posttest for participants tested in later weeks of the study. Mental rotation ability does increase naturally around the developmental ages tested in the present study (Frick, Ferrara, &

Newcombe 2013), so allowing for significantly more time between pretest and posttest may have correlated with children's performance on the CMTT.

Design

The study followed a 2x2 factorial design. The independent variables were the training task completed (either the Mental Rotation challenges or the Building Replication challenges) and whether the children worked in pairs or individually. The dependent variable is the change in performance on the Children's Mental Transformation Task from pretest to posttest, recorded as the difference in points scored.

Both training types included three separate tasks: the Mental Rotation challenges included training sessions with the games Trucky 3, Castle Logix, and Royal Rescue, while the Building Replication challenges involved building with wooden blocks, foam blocks, and Magnatiles.

Materials

Materials for this experiment included three commercially available mental rotation building block challenges (Trucky 3, Castle Logix, and Royal Rescue) as well as three different types of blocks (wooden blocks, foam blocks, and Magnatiles). Cue cards were utilized to ensure that the researcher presented game pieces and blocks to all participants in a consistent arrangement. A timer was used to regulate the amount of time that participants spent on each building challenge, with the maximum time allowed for completion of each challenge being one minute and forty seconds. All training tasks for both the Mental Rotation challenges and the Building Replication challenges consisted of 10 items. Refer to Appendices C and D for full sets of the items used in the Mental Rotation and Building Replication conditions respectively.

In the Mental Rotation challenge condition, cue cards were utilized solely for challenge set-up by the experimenter with the exception of the cards for Castle Logix, which required that children build the castle in the picture utilizing the provided pieces. Trucky 3 included two toy trucks with transparent compartments as well as various blocks of differing shape and color. Royal Rescue utilized two character figurines (a knight and a princess), a stand to keep blocks in place, and different shaped blocks, some of which had sides with steps. Castle Logix utilized castle blocks with holes and different pictures on different sides of the blocks as well as towers of three differing heights.

For the Building Replication items, cue cards consisted of two sides: the fronts of the cards displayed the building that was to be replicated using the blocks and the back of each card showed a template for how the necessary building materials would be presented to participants. The Building Replication tasks were designed to include increasing numbers of blocks to mirror the increasing difficulty in the mental rotation block challenges. The initial challenges consisted of buildings using six blocks, whereas challenges at the end of the session included up to eight blocks.

The pretest and posttest utilized forms of the Children's Mental Transformation Task (CMTT). All items were printed in black and white on 8.5"x11" paper and were presented in three-ring binders. The CMTT consisted of 32 items. The two shapes appeared on the bottom page while the top page was held upright by the experimenter and contained the four answer options. Two forms of this measure were used in the study, each of which had two orders. Each child was randomly assigned a form of the pretest and was tested using the same form with the items presented in reverse order during the posttest. This does not eliminate the possibility that children may have learned specific items from the pretest and applied that knowledge to the posttest, but this seems unlikely as the pretest and posttest were separated by a fairly large period of time. If this study were to be replicated, it would be best to provide children with the items presented in the same order during the posttest, but utilizing a different form to be sure that children were not learning the specific items. Items in the CMTT are presented in four orientations: linear translation, linear rotation, diagonal translation, and diagonal rotation. For a full set of pretest and posttest items, refer to Appendix E.

Figure 1. Example of the presentation of pretest and posttest CMTT items.

Procedure

The study was run using a cohort model as much as was logistically possible with the goal of keeping the intervals between tasks consistent. Approximately four to six children were selected to participate in the study during a given week, with the intention of completing all testing sessions in five consecutive days. Variability occurred based on how many children were participating in pairs and how many were working as individuals, since testing more pairs in a given week allowed for more children to complete the study in that time period. However, this schedule was difficult to maintain given the frequency of absences due to vacations and sickness. The average length of participation was 13.7 days, ranging from a minimum of 5 days to a maximum of 26 days. (Though this range was large, the number of days was not a predictor of improvement on the CMTT. See the Results section for more information.)

For each testing session, participants sat in chairs opposite the experimenter at a table in a small testing room. All testing followed the protocol established by the Children's School ("Carnegie Mellon University Children's School Research Policies 2014-2015," 2014). During the first testing session, all children individually completed the Children's Mental Rotation Task (CMTT). Before completing the task, children were informed that they would see two pieces of paper, one displaying two black shapes and another displaying four answer choices. Participants were instructed to mentally fit the two shapes together to form one of the possible answer choices. (Refer to Appendix F for the complete pretest and posttest script.) After deciding upon an answer, children were asked to point to their answer choice, which was subsequently recorded. The CMTT consisted of 32 trials, with each trial scored for accuracy. This procedure was followed for both the pretest and posttest sessions for each child.

During the three training sessions, children assigned to the "Individual" condition were tested alone while children assigned to the "Collaborative" condition sat in adjacent chairs. Each individual child or pair was randomly assigned to the Mental Rotation challenge condition or the Building Replication challenge condition. Within these conditions, the order of the three training sessions was counterbalanced to prevent order effects.

The Mental Rotation condition involved completing challenges from three different commercially-available games that claim to enhance spatial abilities: Trucky 3, Royal Rescue, and Castle Logix. This condition was run in a very similar manner to the Building Replication condition. To complete each training session, children listened to instructions regarding gameplay (See Appendix G). Children were told not to touch the pieces of the game until the experimenter said to begin and a timer was set at 1 minute and 40 seconds for each challenge. All game pieces were presented in a standardized manner according to the cue cards. The termination of each item was also handled in the same manner as the Building Replication condition. Additionally, children were reminded between items to "think about how the blocks will fit together" and to show the experimenter once they thought they knew how to complete the item.

The Building Replication condition involved replicating building pictures shown on cue cards. At the beginning of each session, participants were informed that for each building challenge, they would be shown a full-color image of a building and would be provided with the blocks that would be necessary to construct the building. Each child or pair was instructed not to touch the blocks until told to begin. To minimize the participants' use of mental rotation, each block was presented to the children in the same orientation that it would face in the final structure. Children were also informed that a timer would run during each building challenge so that there would be time available to attempt every challenge. Children were allowed 1 minute and 40 seconds to attempt each item, which allowed enough time for children to complete all ten items within the 20-minute session while also allowing a buffer for task setup, explanation, and walking participants to and from their classrooms. If the children were not finished when the timer sounded, they were instructed to stop immediately, upon which the experimenter would score their attempt and subsequently demonstrate the correct answer. If the children completed the item with time remaining, they were asked about the certainty of their answer. If the children decided that their answer was incorrect, they were given an additional attempt with the remaining time. If they responded that their answer was correct, I either affirmed or corrected their answer and then scored the child's response. A discussion of the scoring protocol is included below and a complete script for the Building Replication experimental sessions is included in Appendix H.

Scoring

All answers on the pretest and posttest were scored with one point accorded to each correct response. The highest possible score on the CMTT was 32.

The Mental Rotation and Building Replication challenge scores were calculated in a similar manner. For each item, 1 point was scored for every block or game piece that was in the correct location and 1 point was awarded for each piece in the correct orientation. Thus, each piece in a given item could score as low as 0 points (if the piece was both in the incorrect location and was placed in the incorrect orientation) or as high as 2 points (if both location and orientation were correct). Pieces that were not placed when the timer rang were given a score of 0 points. Given these scoring guidelines and the varied nature of the games, the maximum total score was different for each game. The maximum scores are as follows: 46 for Trucky 3, 42 for Royal Rescue, 90 for Castle Logix, 136 for Wooden Blocks, 136 for Foam Blocks, and 134 for MagnaTiles. The minimum score for each training task was 0 points.

The effectiveness of collaboration was not recorded during the experiment, though it was qualitatively assessed[1]. Children were assigned randomly to same-gendered pairs, but some pairs differed radically in terms of collaboration style. For instance, some individuals essentially "took over" the task, relegating their partners to the sidelines; whereas, other children appeared to expect their partners to complete the tasks alone. Some pairs also focused largely on which parts of the task each partner would do, detracting significantly from the time allotted for each problem and resulting in a lower task score.

Results

Children in the Individual Mental Rotation Challenge condition averaged a pretest score of 21 (*SD*= 4.0), a posttest score of 22.1 (*SD*= 2.6), and a score change of 1.1 (*SD*= 3.8). Children in the Collaborative Mental Rotation Challenge condition averaged a pretest score of 18.4 (*SD*= 5.7), a posttest score of 25.6 (*SD*= 4.7), and a score change of 6.5 (*SD*= 6.6). Children in the Individual Building Replication condition averaged a pretest score of 16.6 (*SD*= 6.3), a posttest score of 19.6 (*SD*= 6.1), and a score change of 3.6 (*SD*= 4.4). Children in the Collaborative Building Replication condition averaged a pretest score of 19.7 (*SD*= 6.8), a posttest score of 21.7 (*SD*= 6.1), and a score change of 2.0 (*SD*=2.2). See Appendix I.

There was no significant difference in pretest scores between the conditions, $F\ (3,36) = 0.947$, $p = 0.428$. There was also no significant difference in age between the groups, $F\ (37, 2) = 1.558$, $p = 0.468$.

Values for score change were submitted to a linear mixed hierarchical model, which discovered that the repeated measurements within the collaborative pairs was not significant. As such, the repeated measurements for the collaborative pairs was eliminated and values for score change were submitted to an ANCOVA, with gender and condition as independent variables and score change as the dependent variable, with age, pretest score, and number of days from pretest to posttest as covariates. The test of between-subject effects demonstrated no main effect of condition, $F\ (3,32) = 1.888$, $p = 0.151$, indicating that there was no significant difference in score performance for the four conditions. The effect of gender was statistically significant, $F\ (1, 32) = 5.116$, $p = 0.031$, with $B= -2.98$ with males as the baseline, demonstrating that males improved more from pretest to posttest on the CMTT than females. Pretest score was demonstrated to be a significant predictor of score change, $F\ (1, 32) = 12.491$, $p = 0.001$, with $B = -0.41$, indicating that children with higher pretest scores exhibited less score change than those with lower pretest scores. The number of days between pretest and posttest was not a significant predictor of score change, F (1, 32) = 0.083, p = 0.775. Additionally, age was not a significant predictor of score change, F (1, 32) = 1.346, p = 0.255, though children in the four-year-old class did start at a pretest score 4.292 points lower than the kindergarten students, F (x,x) = 0.130, p = 0.027. Score change in the Collaborative Mental Rotation condition approached significance when compared with the Collaborative Building Replication condition, B = 3.211, p = 0.074. Score change was not significantly significant between the collaborative conditions and the individual conditions, F (1, 35) = 1.179, p = 0.285.

Additionally, a paired t-test demonstrated that posttest scores (M = 22.14, SD = 5.579) were significantly higher than pretest scores (M = 19.03, SD = 6.211), t(36) = 3.878, $p < 0.001$. Mean score improvement from pretest to posttest was 3.108 points.

Discussion

The results of the present study suggest that young children do in fact achieve improved mental rotation skills by engaging in current commercially available mental rotation block challenges, but that this improvement is also demonstrated upon completion of building block replication tasks. There was no significant difference in improvement on the CMTT between the four conditions, though the results demonstrated that the differences in score change between the Collaborative Mental Rotation condition and the Collaborative Building Replication condition were nearing significant levels, with children in the Collaborative Mental Rotation condition improving more on the mental rotation task than those in the Collaborative Building Replication condition. Though this result was not significant, perhaps a larger sample size would demonstrate more clear differences between the groups. Furthermore, the data do not support prior research that claims the effectiveness of collaborative learning over individual learning, as children in the collaborative conditions did not improve on the mental rotation task more than the children who worked as individuals. Additionally, it was discerned that males were not more adept at mental rotation tasks than females either at pretest or posttest, as has been suggested in numerous previous studies, but that gender was a significant predictor of score change from pretest to posttest, with males improving at a greater rate than females.

There are, however, considerations to be made when assessing the results of this study. Though collaboration style was not recorded, it appeared that pairs varied widely in this regard, and this variability may have influenced the efficacy of collaboration. [2]Because children were randomly assigned to pairs, they may or may not have been working with partners that they would typically collaborate with by choice. Arguments that arose during testing sessions might be avoided in the typical classroom environment, where children are able to choose with whom to play and work. One can argue, though, that collaboration throughout the life span is often determined arbitrarily through assigned partners for group projects and coworkers in the same department. Thus, random assignment may well mimic the collaborative situations in which children will be involved over time. If the study had been conducted with a larger sample size, it would likely be beneficial to categorize children based on collaborative style to determine whether certain collaborative strategies are more beneficial when engaging in these educational games.

It is encouraging that results indicated an overall improvement in mental rotation ability following engagement in the three mental rotation games used in this study. It is important to note though that the games played by children in the Mental Rotation condition were all marketed as logic-based spatial awareness games, but were somewhat different in terms of their demands. Because the children in the Mental Rotation condition played all three games, the efficacy of each individual game cannot be disentangled from the others. Thus, it is difficult to determine whether a single game would improve mental rotation ability. However, it is important to note that children have differing strengths and in that sense, having multiple games targeting the same skill was likely beneficial to the study. It may be impractical though to assume that children would engage in three different spatial awareness games outside of a laboratory setting. Thus, this study should be evidence that these games *can* improve a child's mental rotation ability, but that buying these games for a child may not produce such results if the games are played individually. Additionally, since experimental sessions were limited to only twenty minutes, more robust improvement in mental rotation ability may be demonstrated if a child played one game for a more extended period of time, such as at home, in order to reach the more challenging levels that come later in the game.

Notably, children's mental rotation ability also increased after engaging in the building replication tasks. Though this was not predicted prior to the study, this phenomenon may be explained by the fact that the tasks were likely not devoid of mental rotation demands. Even though blocks were presented to the children in a manner that was designed to decrease mental rotation (i.e., all blocks were presented in the orientation that they would be placed in the completed building), children often rotated the blocks before adding them to the structure. Additionally, it is possible that moving the blocks to a three-dimensional structure may have also strengthened mental rotation ability.

The external validity of the results may also be uncertain. The sample size was relatively small, and the students at the Children's School may also have characteristics that differ from the general population (e.g., many high SES families, families that may already encourage these sorts of enrichment games, etc.). Children who play similar games in the home are likely to have a higher initial ability on mental rotation tasks and as such, less room to improve. In addition, the children at the Children's School are used to participating in research and in similar games in the classroom, so they may have begun with higher than average performance on the CMTT, also leaving less room for improvement on the task.

Though this study does not demonstrate that mental rotation block challenges are more effective than building replication challenges, it is encouraging that results show both tasks to increase mental rotation ability, especially since building block replication tasks are so accessible. These tasks can be enjoyed at home with children mimicking a block structure created by the parent, making it a task open to endless variation. Additionally, even though the study does not suggest that collaborative learning of mental rotation is superior to individual learning of the concept, this possibility should not be discounted. Future studies may benefit from examining the difference between individual and collaborative learning of mental rotation with a more narrow focus. For instance, a study examining the difference in collaborative versus individual learning of mental rotation using only mental rotation games without building replication tasks may prove to illustrate the potential benefits of collaborative learning. Additionally, it would be interesting to conduct a similar study with a single game, but still played over a series of sessions. If each mental rotation block task were tested in this manner, it would be more feasible to determine whether each is effective in its own right. Finally, it would likely be beneficial to examine these games with finer-grained precision. It may be beneficial to examine the strategies being used to solve the tasks to determine whether or not they are actually applicable to performance on the Children's Mental Transformation Task. It is possible that children use different strategies for the different tasks and that some of these strategies are more applicable to success on the CMTT than others. Also, additional research may benefit from the use of a more comprehensive battery of tests to determine whether these tasks improve other components of spatial awareness besides mental rotation.

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Appendix A

Carnegie Mellon University

Institutional Review Board
Federalwide Assurance No: FWA00004206
IRB Registration No: IRB00000603

Office of Research Integrity and Compliance (ORIC)
Carnegie Mellon University
5000 Forbes Avenue
Warner Hall, 4th Floor
Pittsburgh, Pennsylvania 15213-3890
412.268.7166
irb-review@andrew.cmu.edu

Certification of IRB Approval

IRB Protocol Number: HS14-767
Title: Effects of Individual Versus Collaborative Logic-Based Spatial Exercises on Individual Spatial Visualization Ability
Investigator(s): Ashley Taylor and Sharon Carver
Department(s): Psychology
Date: January 13, 2015

Carnegie Mellon University Institutional Review Board (IRB) reviewed the above referenced research protocol in accordance with 45 CFR 46 and CMU's Federalwide Assurance. The research protocol has been given **APPROVAL by Expedited Review on January 12, 2015, as authorized by 45 CFR 46.110 (7) and 21 CFR 56.110. This APPROVAL expires on January 11, 2016,** unless suspended or terminated earlier by action of the IRB.

All untoward or adverse events occurring in the course of the protocol must be reported to the IRB within three (3) working days. Any additional modifications to this research protocol or advertising materials pertaining to the study must be submitted for review and granted IRB approval prior to implementation. Please refer to the above-referenced protocol number in all correspondence.

Federal regulations require that all records relating to this research protocol be maintained for **at least three (3) years after completion** of the research, and be accessible for inspection and copying by authorized representatives at reasonable times and in a reasonable manner.

The Investigator(s) listed above in conducting this protocol agree(s) to follow the recommendations of the IRB and the Office of the Provost of any conditions to or changes in procedure subsequent to this review. In undertaking the execution of the protocol, the investigator(s) further agree(s) to abide by all CMU research policies including, but not limited to the policies on responsible conduct research and conflict of interest.

The IRB maintains ongoing review of all projects involving humans or human materials, and at continuing intervals, projects will require update until completion. At the end of the current approval, a continuing review form, current application/protocol and current consent form(s) must be submitted by the PI to the IRB summarizing progress on the protocol during that period. Please be advised that the continuing review form requests information pertaining to women and minorities; therefore, this information should be tracked with your participants' data. **Note that submitting for continuing review in a timely manner is the responsibility of the PI.**

Please call the Office of Research Integrity and Compliance at 412-268-7166 if you have any questions regarding this certification. Thank you.

John Zimmerman, IRB Chair

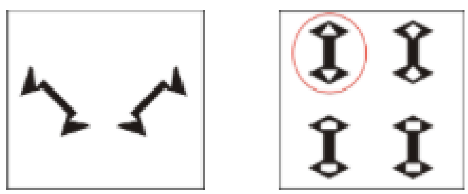
IRB Approval Letter

Appendix B

Playing the Construction Game at the Children's School!

Think of a letter (for instance, a capital "E"). If you were instructed to flip the letter upside down, or rotate it 90°, you would likely be able to visualize how the letter would change. Young children, on the other hand, often have difficulty with this task, as they are not yet skilled in using *mental rotation*. The ability to manipulate an image in one's head has been shown to correlate with success in fields such as math and science, so it stands to reason that children who practice this skill early on will be at an advantage in future learning.

The goal of this study is to examine how working with a partner on a game that requires the use of mental rotation affects an individual child's ability to employ mental rotation in future tasks. Simply put, does working with a peer help to increase a child's ability to understand future mental rotation tasks? To examine this topic, children have been assigned to work either *individually* or *with a friend* to complete tasks: either commercially-available games that require the use of mental rotation strategies (Trucky 3, Royal Rescue, and Castle Logix) or "building replication" tasks designed to employ the same building skills as the games, but without requiring mental rotation ability. Within these four conditions, children will participate in three brief, 15-minute sessions to practice their skills. Children's mental rotation abilities will be assessed before and after these practice sessions using the Children's Mental Transformation Task (CMTT) and the Ghost Puzzle task. During the CMTT, children will be shown an image of two shapes and asked which of the four answer options can be made by putting the two shapes together. (See below for a sample question.) In the Ghost Puzzle task, children will be shown two ghosts which are mirror images of each other and will be asked which ghost is able to fill the black space on a separate sheet of paper.



"If you had two puzzle pieces just like these, which of these shapes could you make if you put them together?"
(Answer circled on right.)

Royal Rescue

Trucky 3

Castle Logix

Researchers: Ashley Taylor & Dr. Sharon Carver

Participant: ___________________________________

Parent Description

Note that the above Parent Description references the Ghost Puzzle, which was discontinued midway through the study.

Appendix C
Mental Rotation Challenge Items

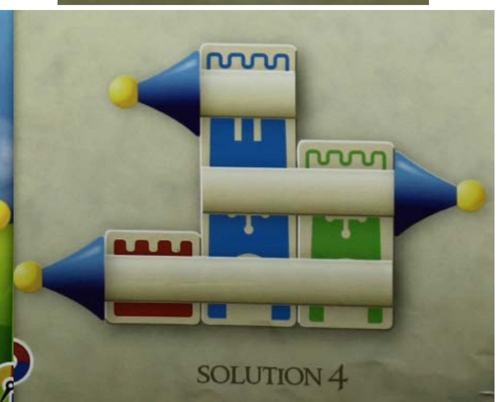
The following items were used as the Mental Rotation tasks. The first task in each set was an example task, used to demonstrate how to play each game. The subsequent items were completed by the participants. The left picture is the task presented to participants and the right picture is the solution to each item.

Castle Logix


CHALLENGE 3


SOLUTION 3


CHALLENGE 4


SOLUTION 4


CHALLENGE 5


SOLUTION 5


CHALLENGE 6


SOLUTION 6


CHALLENGE 7


SOLUTION 7


CHALLENGE 8

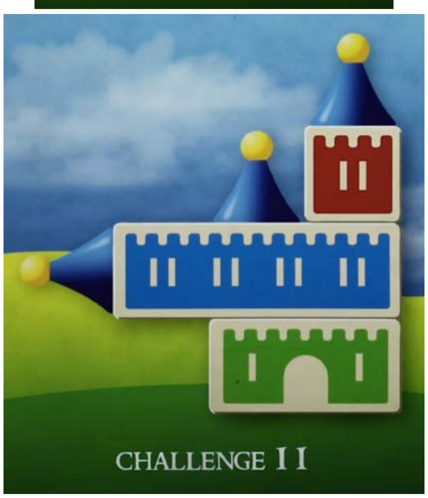

SOLUTION 8


CHALLENGE 9


SOLUTION 9

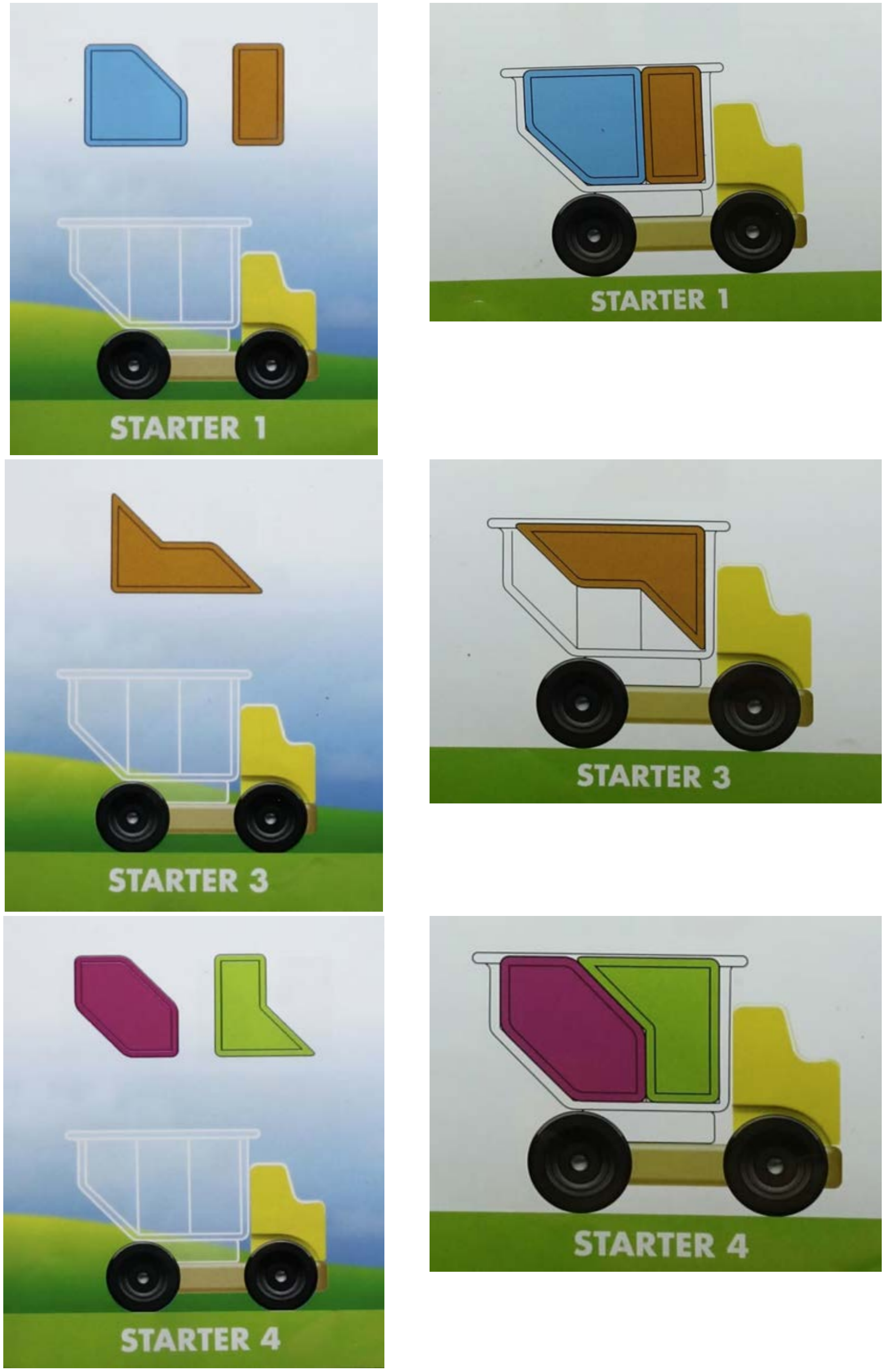

CHALLENGE 10


SOLUTION 10


CHALLENGE 11


SOLUTION 11

Trucky 3




STARTER 5


STARTER 5


STARTER 6


STARTER 6


STARTER 7


STARTER 7


STARTER 8

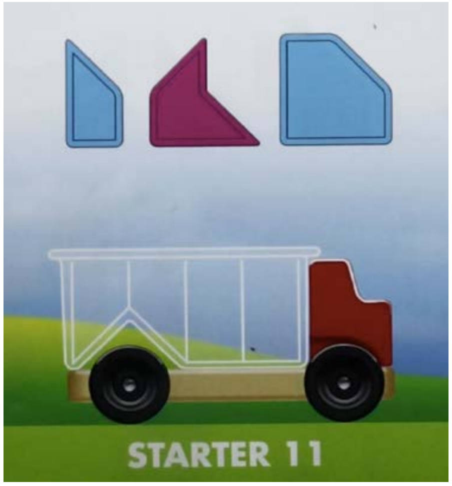

STARTER 8


STARTER 9

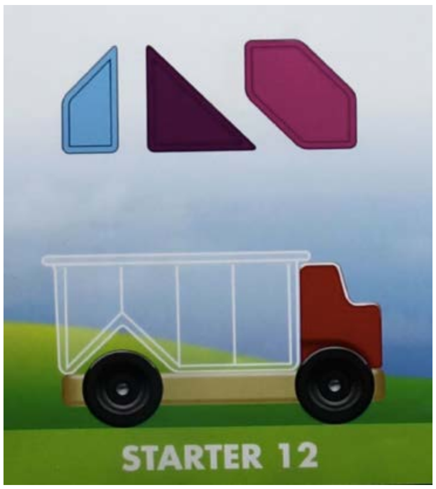

STARTER 9


STARTER 10


STARTER 10

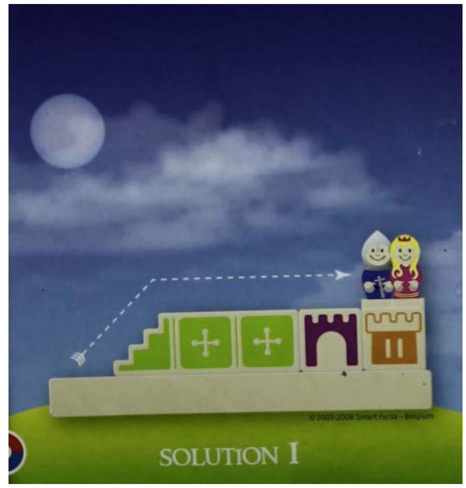

STARTER 11

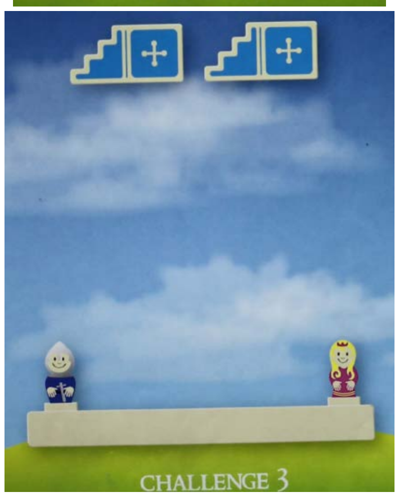

STARTER 11

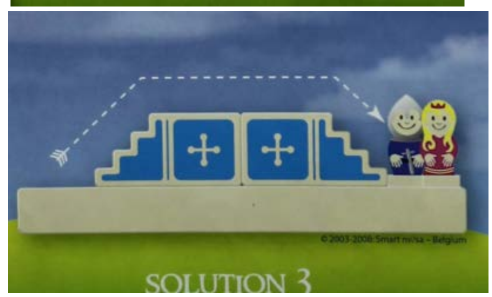

STARTER 12

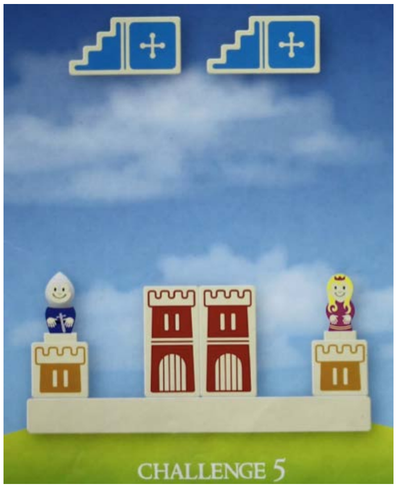

STARTER 12

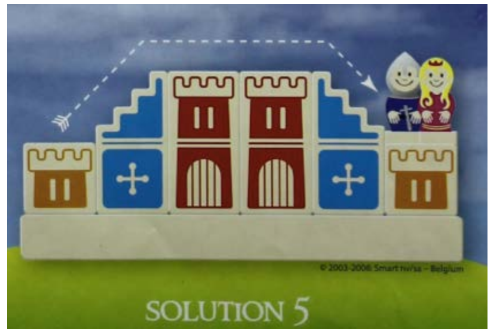
Royal Rescue

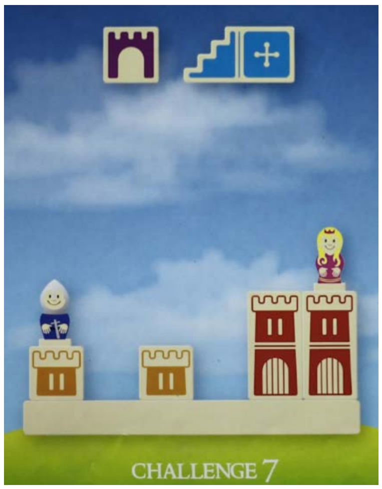







CHALLENGE 5


SOLUTION 5


CHALLENGE 7

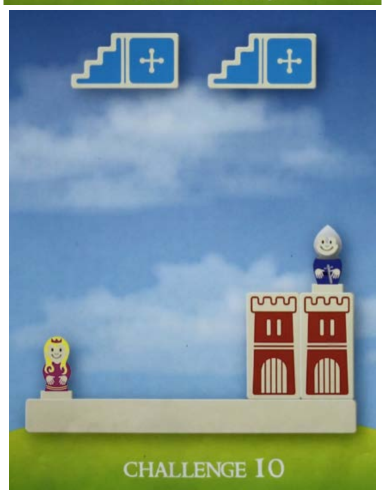

SOLUTION 7

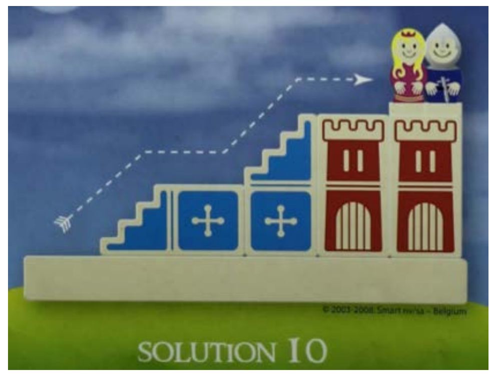

CHALLENGE 8


SOLUTION 8


CHALLENGE 9


SOLUTION 9


CHALLENGE 10

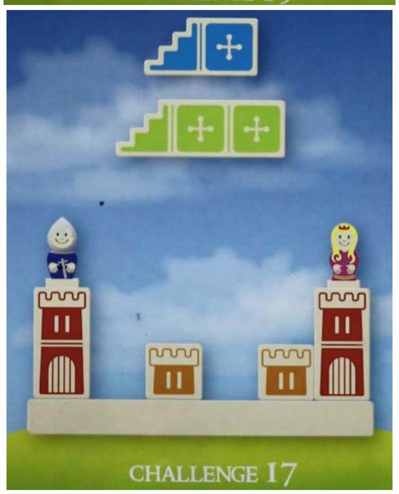

SOLUTION 10

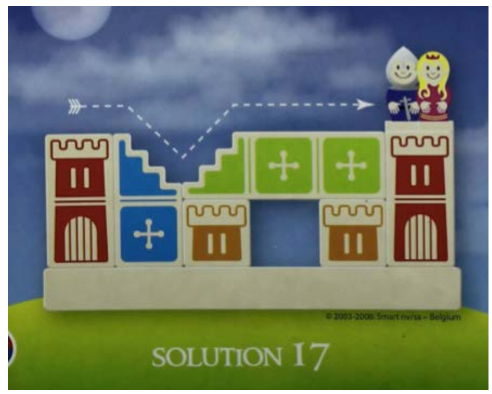

CHALLENGE 11


SOLUTION 11


CHALLENGE 13


SOLUTION 13

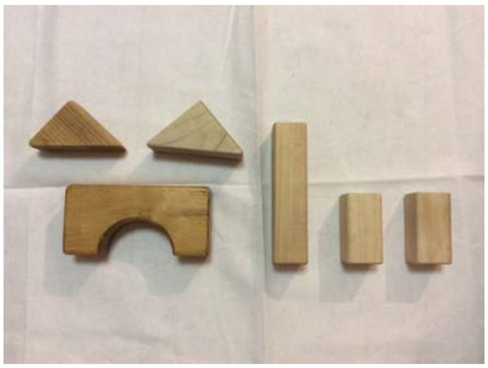

CHALLENGE 17

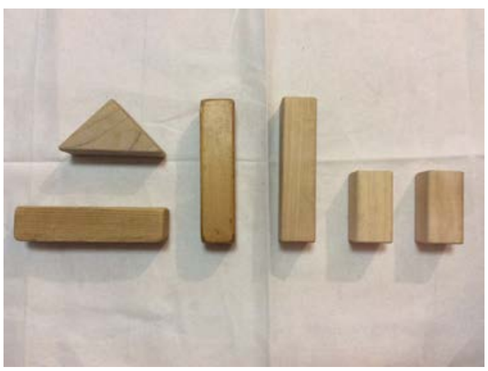

SOLUTION 17

Appendix D
Building Replication Challenge Items

The following items were used as the Building Replication tasks. Presented on the left is the block layout used by the experimenter to present the blocks to the participant. On the right is the building that participants were asked to replicate.

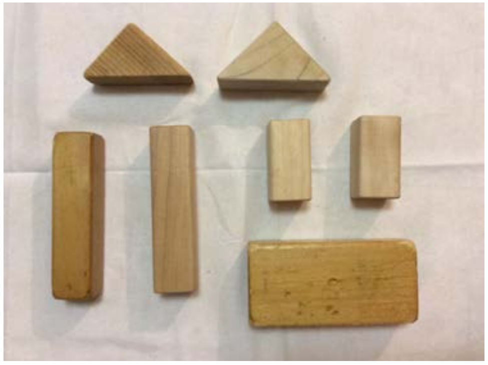
Wooden Blocks



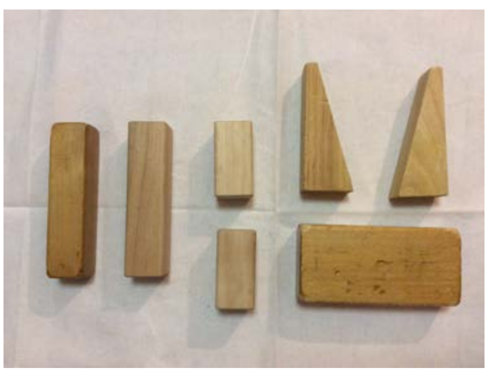


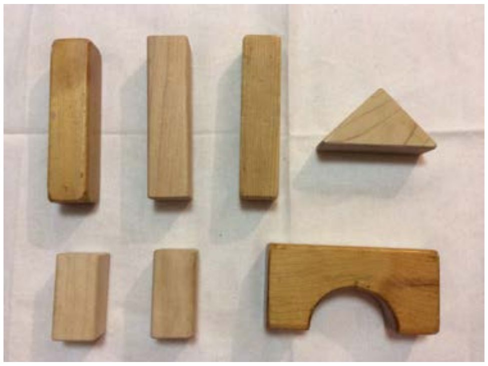




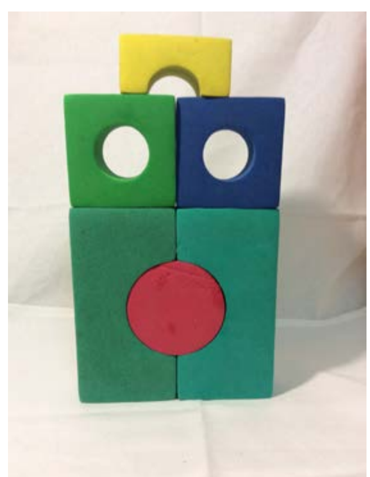



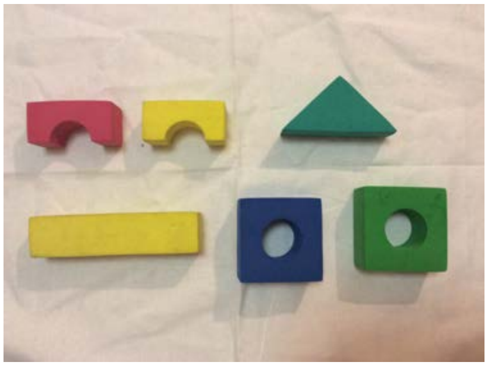


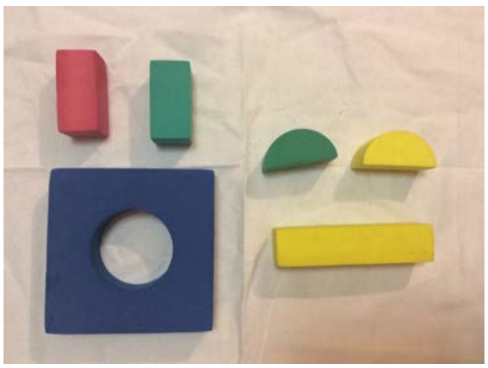


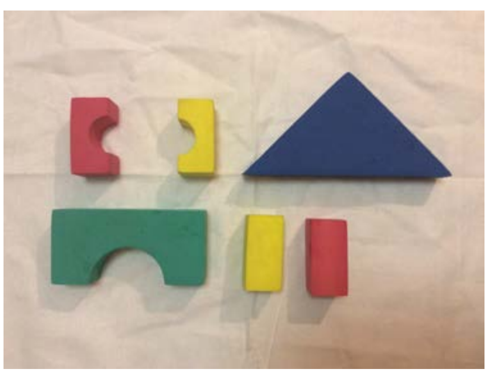



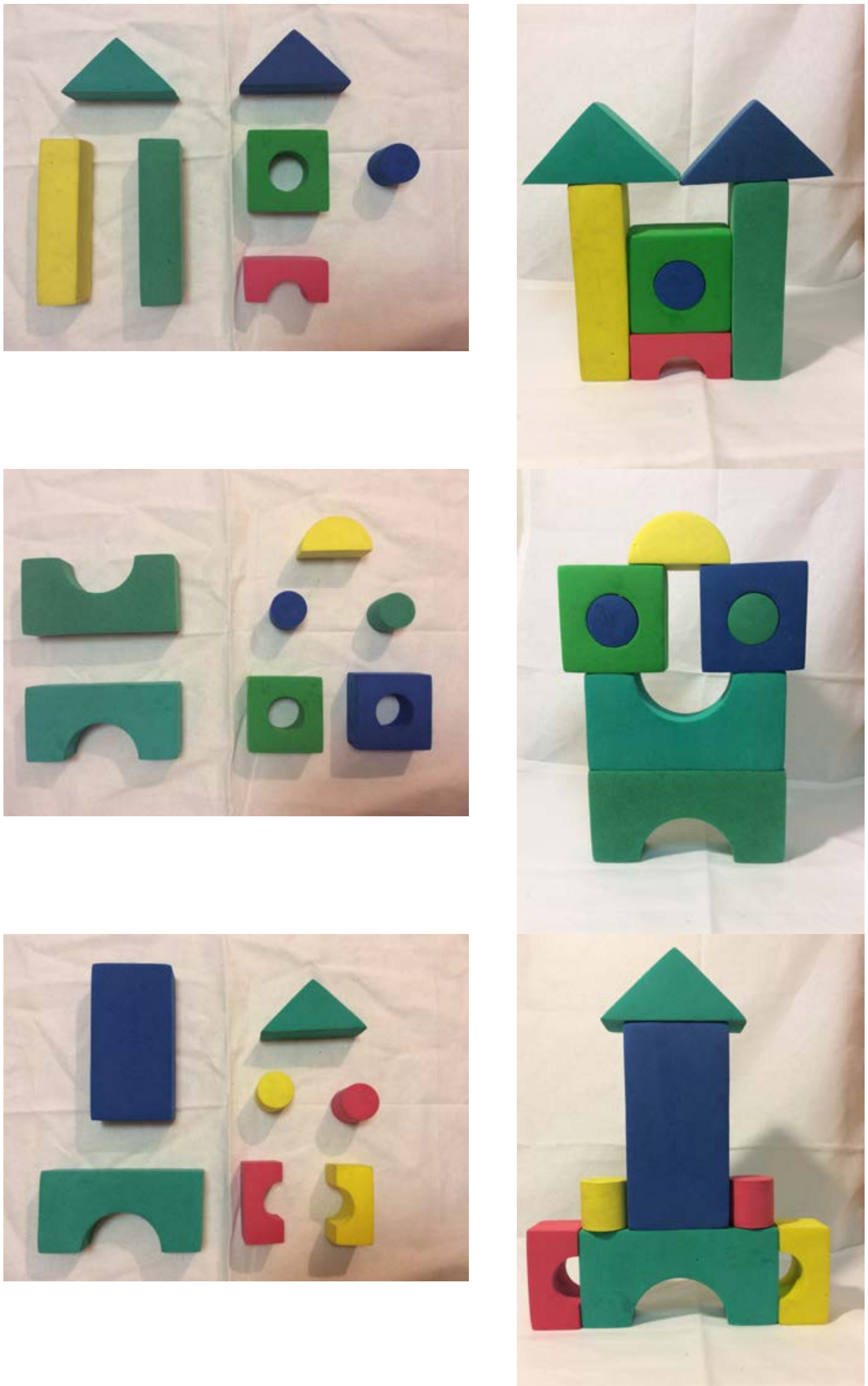
Foam Blocks

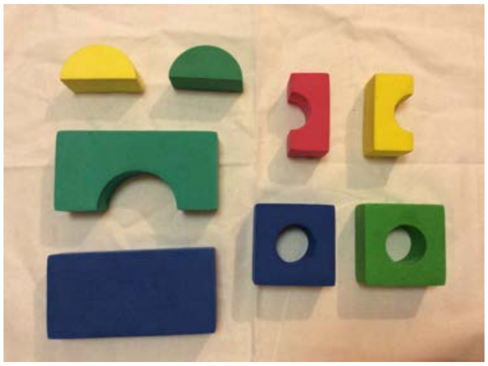


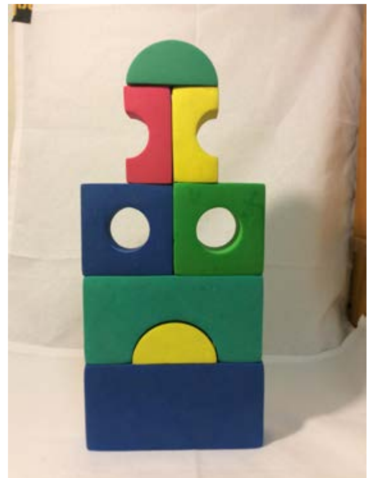


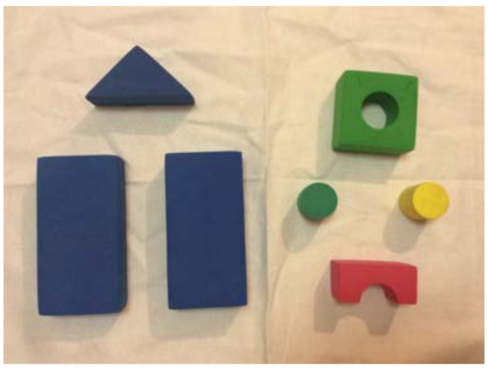


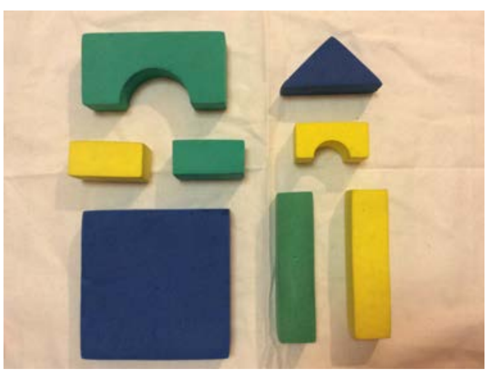


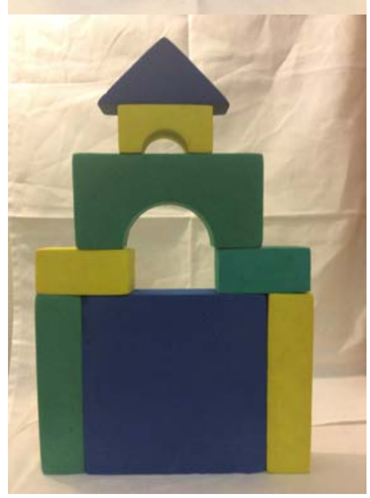




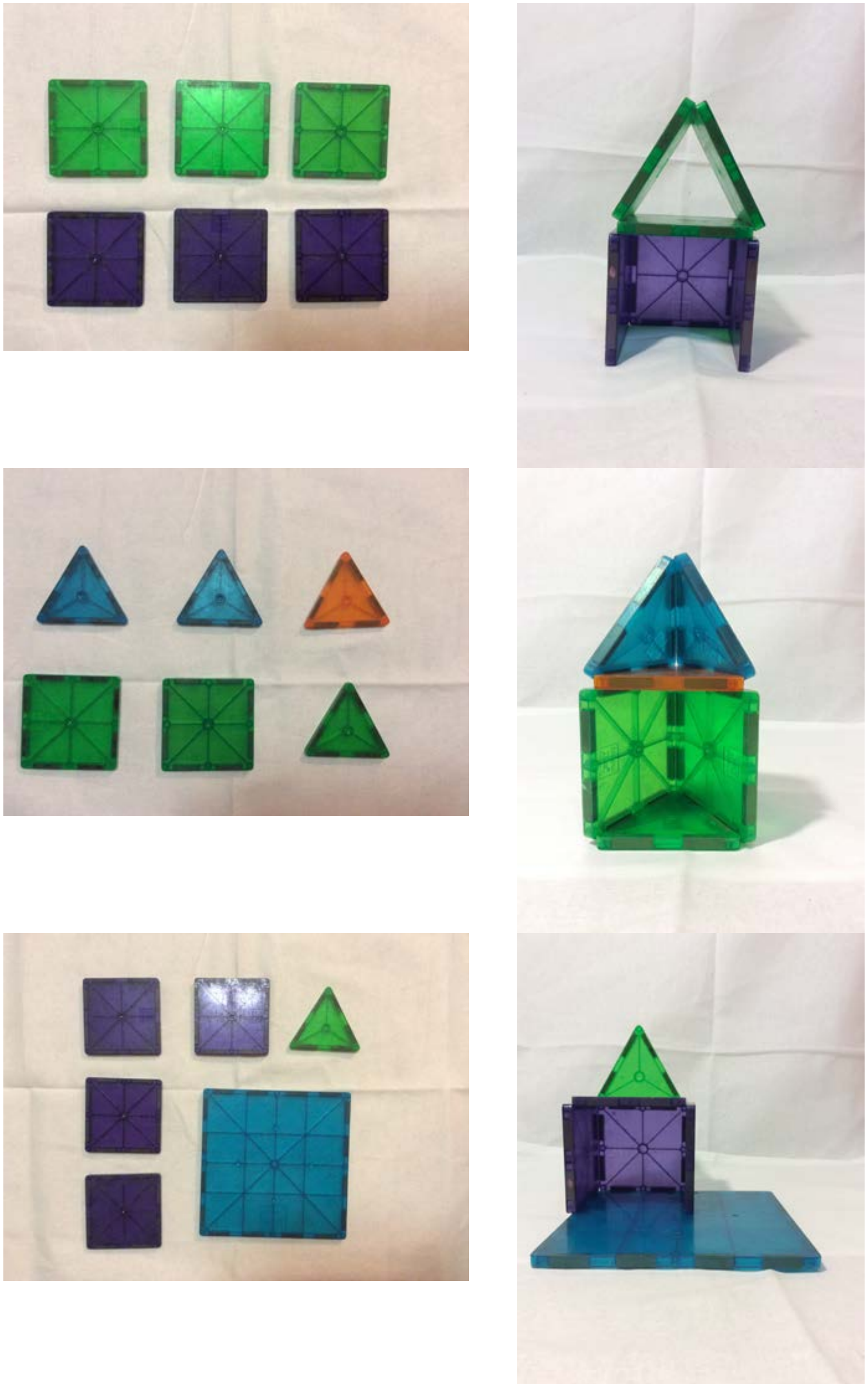


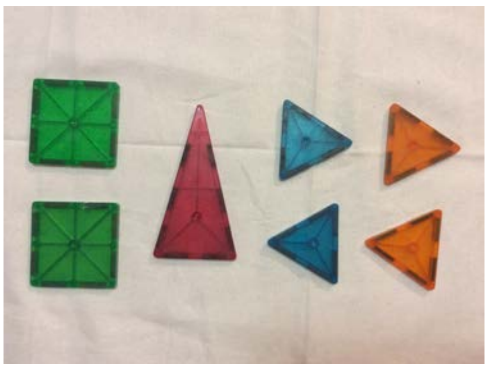


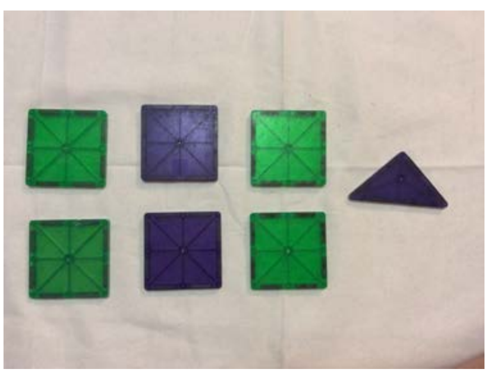


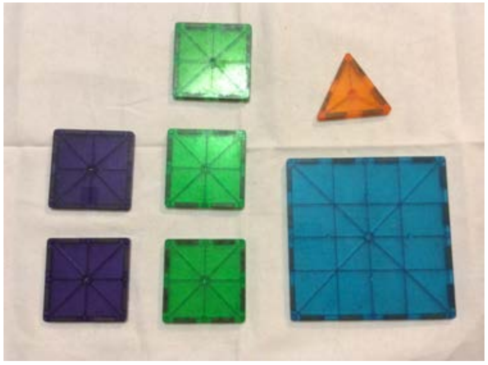
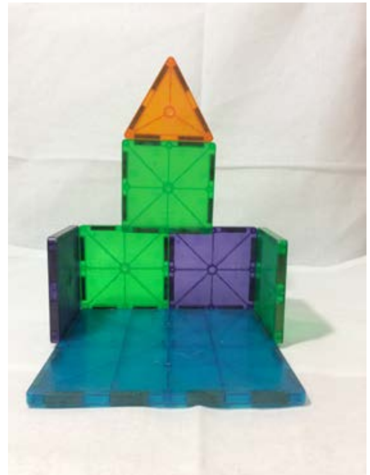
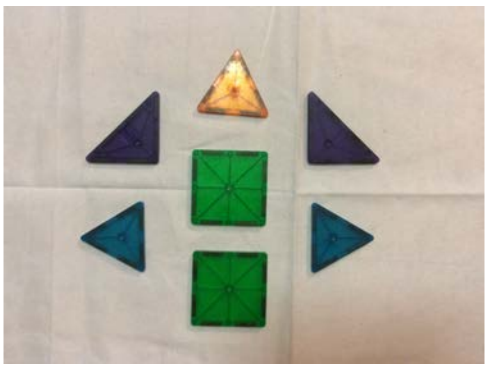


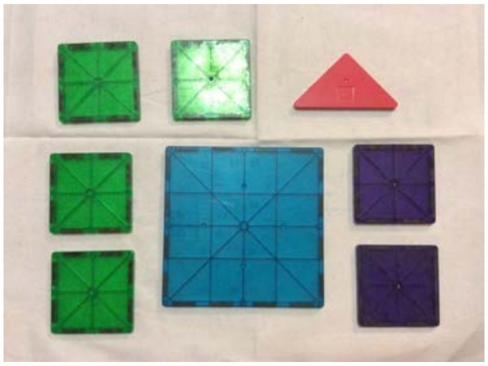
MagnaTiles

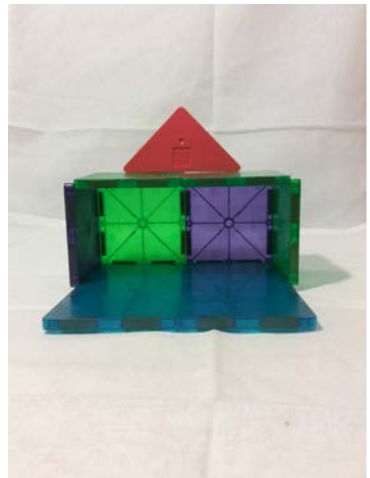






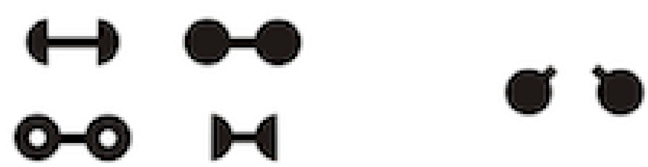
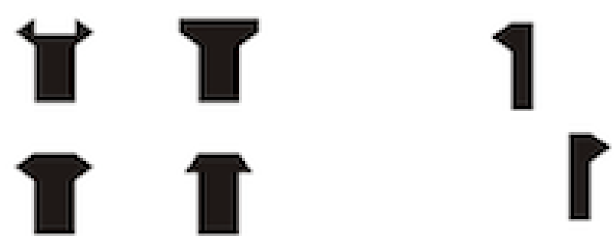






Appendix E
Children's Mental Transformation Task

Presented below are sample items from Levine, Huttenlocher, Taylor, & Langrock's 1999 Children's Mental Transformation Task. A complete set of items used in the present study is available for download at the Spatial Intelligence and Learning Center's website at http://spatiallearning.org/index.php/resources/testsainstruments under the heading "Children's Mental Transformation Task." The present study utilized both orders of Forms A and B.

Horizontal Translation	
Horizontal Rotation	
Diagonal Translation	
Diagonal Rotation	

Appendix F
Pretest & Posttest Script

Introduction

“Okay, _(name)_. Today we’re going to play the Puzzle Game. When we play the Puzzle Game, I’m going to show you a paper with two shapes on it and another paper with four picture choices on it. Your job is to try to put the two pieces together in your head so that they look like one of the four pictures that I show you. When you put them together in your head, it’s your job to tell me which of the four shapes they make. When you know the answer, please point to it for me, okay? Now that you know the rules, let’s play the Puzzle Game!”

Before each question, ask a variation of the following:

“What shape will these two pieces make when you put them together in your head?”

or

“What about these two shapes?”

Conclusion:

“Great job playing the Puzzle Game!”

Appendix G
Mental Rotation Challenge Script

"Okay, _(name)_. Today we're going to play a game called…"

Castle Logix

"In this game, I'm going to give you six pieces: three of them are towers and three of them are buildings. I'm also going to show you some pictures of castles. Your job is to use the pieces you have to build the castles in the pictures, okay? Sometimes the castles are a bit tricky to build, though, because some spots in the building blocks have holes, but other spots don't." (Demonstrate how a tower might "stick up" if it hits a block that doesn't have a hole.) Let me show you an example. (Demonstrate with example challenge.) "For every question, I want you to think very carefully about how the blocks will fit together. Please don't touch the blocks until you think you know how to put the castle together. Then, when you think you know the answer, you can show me how to do it." (See below.)

Royal Rescue

"In this game, we have a knight and a princess, but they're far apart. Your job is to help them get to each other. To do that, I'm going to give you a few blocks, and you have to put them between the knight and the princess so that they can walk to each other. There are a few things the knight and princess can't do, though. They have to walk on the flat sides of the blocks or on the stairs. It's okay to turn a block so the stairs are upside down, but the knight and princess can't walk upside down. The knight and princess can't jump, so they have to use the stairs to go up and down. You can't put the blocks on the pointy edges, only on the flat sides. Also, your bridge has to be strong, so the knight and princess don't fall off." (Show an example of an unstable structure.) And one more rule: You have to use all of the blocks that I give you. Let me show you an example. (Demonstrate with example challenge.) Now that we know the rules, this is how we'll play: For every question, I want you to think very carefully about how the blocks will fit together. Please don't touch the blocks until you think you know how to make the bridge. Then, when you think you know the answer, you can show me how to do it." (See below.)

Trucky 3

"In this game, we have some trucks that need to be packed. To play the game, I will give you one truck and a few blocks that need to fit inside it. The only rule for loading the truck is that no blocks can stick out of the top. Let me show you an example of how to pack one of the trucks. (Demonstrate with example challenge.) For every question, I want you to think very carefully about how the blocks will fit together. Please don't touch the blocks until you think you know how to pack them in the truck. Then, when you think you know the answer, you can show me how to do it." (See below.)

"Do you have any questions about how to play the game?" *(If so, answer using script if possible.)*

"One more rule before we start: For each challenge, I'm going to set a timer because I want us to have time to try every challenge. If you run out of time, the timer will play music. If you hear the music, I want you to stop working right away and then I will show you how to finish the challenge. After I show you the answer, we'll try the next challenge, okay? Let's get started."

Between trials, remind children to think about how to move the blocks before they actually move them. If they are working with a partner, remind them to "work together as a team."

If the timer goes off before the child is finished:

"Oh, it looks like we ran out of time. Let me show you how I would finish the challenge."

If challenge completed before timer sounds:

"Does that look like the right answer?"

End of game:

"You did a great job playing my game, _(name)_! Thank you for playing!"

Standard Encouragements:

"We're almost (or "halfway") done! Let's keep going."

"Let's make sure to stay focused on the challenges, okay?"

"We're very close. Keep up the good work!"

Appendix H
Building Replication Challenge Script

"Okay, _(name)_. Today we're going to play a game called the (Foam Block, MagnaTile, Wooden Block) Construction Game. I'm going to give you a few blocks and I'm also going to show you some pictures of buildings. Your job is to use the blocks to make the buildings in the pictures that I show you. To play the game, I'm going to give you the blocks. Then I'm going to show you a picture of a building I want you to make. But before we start, I have a few rules for our game. My first rule is "Please don't touch the pieces until I say 'Go.'" My second rule is that I want your buildings to look exactly like the picture, so look at the picture closely when you're building. And my third rule is that for each building challenge, I'm going to set a timer because I want us to have time to try every challenge. If you run out of time, the timer will play music. If you hear the music, I want you to stop working right away and then I will show you how to finish the challenge. After I show you the answer, we'll try the next challenge, okay? Do you have any questions about how to play my game?" (*If questions arise, answer using script if possible.*)

"Okay, let's get started!"

"Here are the blocks we need for the (first, next, or last) building." *(Lay out blocks in standard orientation.)*

"Remember, try to make your building look exactly like the picture, okay? Go!"

--Child completes item--

If timer goes off:

"Oh, it looks like we ran out of time. Let me show you how I would finish the building."

If complete before timer sounds:

“Look closely at your building. Does it look exactly like the picture?”

“Okay, thanks _(name)_. Here’s our next challenge.”

End of game:

“You did a great job playing my game, _(name)_! Thank you for playing!”

Standard encouragement phrases:

“We’re almost (or “halfway”) done! Let’s keep going.”

“Let’s make sure to stay focused on the challenges, okay?”

“We’re very close. Keep up the good work!”

Appendix I
Scores by Condition

	Average Pretest Score	**Average Posttest Score**	**Average Score Change**
Individual Mental Rotation	21.0	22.1	1.1
Collaborative Mental Rotation	18.4	25.6	6.5
Individual Building Replication	16.6	19.6	3.6
Collaborative Building Replication	19.7	21.7	2.0