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Imagining a Way Out of the Gravity Bias: Preschoolers Can Visualize the Solution to a Spatial Problem

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Abstract

Can young children visualize the solution to a difficult spatial problem? Forty-eight 3-year-olds were tested in a spatial reasoning paradigm in which they were asked to predict the path of a ball moving through one of three intertwined tubes. One group of children was asked to visualize the ball rolling down the tube before they made their predictions, a second group was given identical instructions without being asked to use visual imagery, and a third group was given no instructions. Children in the visualization condition performed significantly better than those in the other conditions, suggesting that encouraging young children to use visual imagery may help them to reason through difficult problems.

The ability to engage in visual imagery—to mentally represent an object or an event that is not physically present—is one of the most powerful operations in human cognition. It is particularly useful for problem-solving because it allows one to try out solutions before committing to a particular course of action. For example, in arranging furniture in a small room, it is helpful to be able to imagine whether a configuration is possible before actually moving things around. Adults' ability to use and benefit from visual imagery is clear and well-documented (e.g., Cooper, 1975; Driskell, Copper, & Moran, 1994; Kosslyn, 1978; Shepard & Metzler, 1971; Vieilledent, Kosslyn, Berthoz, & Giraudo, 2003). Here, we asked whether young children can also benefit from visualizing a solution to a difficult problem.

Much of the previous work on imagery in children has focused not on whether they can use it for imagining solutions to problems, but on whether they can use it to mentally rotate objects (e.g., Funk, Brugger, & Wilkening, 2005; Krüger & Krist, 2009; Marmar, 1975) or to map the location of an object in a familiar room to the corresponding location in a novel room (Reiser, Garing, and Young, 1994). One line of research has demonstrated convincingly that children can use imagery to solve a particular kind of logic problem. Dias and Harris (1988, 1990) provided 4- to 6-year-olds with counterfactual statements (e.g., "all fishes live in trees"), and asked them to engage in syllogistic reasoning about a specific example ("Tot is a fish. Does Tot live in water?"). Children were more likely to respond correctly ("No. Because you told me that fishes live in trees.") if they were instructed beforehand to pretend that they lived on a different planet or to "make a picture" of the situation in their heads (see also Richards & Sanderson, 1999). Even in these studies, however, the focus was not on children's use of imagery to visualize a solution to a problem, but on their use of imagery to enter a fantasy world where a counterfactual statement could be true.

The purpose of the current study was to examine young children's use of visual imagery for problem-solving. We adapted a spatial reasoning paradigm in which preschoolers observe an experimenter drop a ball down one of three tubes and are then asked to search for the ball (Hood, 1995). As shown in Figure 1, to find the ball, children need only to follow the path

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of the relevant tube. However, young preschoolers rarely succeed and instead show a highly robust “gravity bias.” They repeatedly search for the ball in the location directly beneath the opening through which it was dropped, demonstrating that they expect it to fall straight down. The gravity bias is so compelling that children under about 4 years of age are unable to overcome it even after extensive training (Hood, 1995) and it is shared by non-human animals such as cotton-top tamarins, dogs, and chimpanzees (Hood, Hauser, Anderson, & Santos, 1999; Osthaus, Slater, & Lea, 2003; Tomonaga, Imura, Mizuno, & Tanaka, 2007)

We used the tubes task because it is especially conducive to visualization—there are only three possible tubes to track, the tubes are intertwined but not entangled and thus visually distinct, the tubes lead to only three possible outcomes, and successful performance requires visualizing a novel spatial event. We tested 3-year-old children because they can understand instructions to use their imagination (Reiser et al., 1994; Richards & Sanderson, 1999) and because they consistently commit gravity bias errors (Hood, 1995). We asked children to “imagine” an event rather than to “visualize” it because of their presumed familiarity with the word “imagine.” To further increase the effectiveness of visualization, we asked participants to predict where they thought the ball would emerge rather than asking them to search for it as in previous studies (e.g., Hood, 1995). The primary variable of interest was whether encouraging children to use their imagination would lead them to correctly predict the location where the ball would emerge when dropped.

The imagine instructions imposed a brief time delay before each response, raising the possibility that the delay, not visual imagery, would help children to inhibit the prepotent gravity bias (see Diamond, Kirkham, & Amso, 2002). Indeed, developments in inhibitory control are thought to allow children to overcome the gravity bias (Freeman, Hood, & Meehan, 2004); older children who typically do not make gravity errors resume making them if their inhibitory control is taxed (Hood, Wilson, & Dyson, 2006). To control for the delay, we tested a second group of children in a “wait condition” in which all procedures and instructions were identical to the first condition, except the children in this condition never heard the word “imagine.” Finally, to control for the possibility that hearing additional instructions of any kind could affect performance, a third group of children participated in a “control condition” in which they were asked to predict the location of the ball without any additional instructions.

We also sought to compare the effects of visual imagery with those of visual feedback by presenting two types of test trials. On half of the trials, the tubes were transparent and on the other half, they were opaque. Half of the children in each instruction condition received the transparent tube trials before the opaque tube trials, and vice versa. The transparent tubes provided children with an opportunity to learn about the falling event as they saw a ball moving through a particular tube and coming out of the connected opening. In contrast, the opaque tubes occluded all information about the ball's movement. Of interest was whether children who received the transparent tube trials first (and so received visual feedback on their predictions) would perform better than the children who received the opaque trials first.

We predicted that if young children can visualize the solution to a spatial problem and can benefit from doing so, then those invited to imagine the trajectory of a ball should respond more accurately than children in the wait and control conditions, who should make primarily gravity bias errors (Hood, 1995, 1998). Additionally, if visual feedback is as effective as visual imagery, then the children who were first given a chance to learn about the mechanics of the falling event via transparent tube trials should perform better than those who began the test session with opaque tube trials, even if they were not explicitly encouraged to use their imagination to solve this spatial problem.

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Method

Participants

Forty-eight 3-year-olds (*M* age = 39.32 months, *SD* = 2.58; 22 boys) participated in the current study. All children were born at term and most came from White, middle class families. Children received a small gift (e.g., t-shirt, ball) for their participation. Three additional children were excluded from the final sample because they refused to complete the session.

Apparatus

As shown in Figure 1, a large wooden frame (61 cm high, 55 cm wide, 12 cm deep) was constructed to contain three openings each in the top and bottom braces (modeled after Hood, 1995). The openings were spaced at equal intervals. Flexible tubes (6 cm wide, approximately 60 cm long) were attached between the openings in the two braces to create a pathway for a small foam ball. On half the trials (opaque tube trials), the tubes were made of black duct tubing; on the other trials (transparent tube trials), they were made of transparent PVC wall hoses. The tubes were similar in appearance and differed in transparency only. The configuration of the tubes is shown in Figure 1.

Design

Participants were assigned to imagine, wait, or control instruction conditions (each n = 16). In the *imagine condition*, on each test trial, children were asked to use their imagination before making a prediction about where the ball would land ("Can you imagine the ball rolling down the tube?"). In the *wait condition*, before each prediction, children were told that the ball was going to roll down the tube ("The ball is going to roll down the bumpy tube."). The prompts in the two conditions were approximately the same length and used as much of the same key words as possible ("ball," "roll," "tube"). Finally, in the *control condition*, children were simply asked to predict the final location of the ball without any additional instructions.

Half of the participants in each instruction condition received *transparent tube trials* before *opaque tube trials*, and the other half received the reverse.

Procedure

Familiarization—As in Hood (1995), children were first familiarized with the components of the task separately. First, the experimenter and child took turns rolling a ball through a horizontally oriented tube. In the imagine condition, before rolling the ball through the tube, the experimenter said, "Have you ever used your imagination? Before I drop the ball, let's imagine the ball as it rolls down the tube," before gazing at the tube for a few seconds to demonstrate. In the wait condition, before rolling the ball through the tube, the experimenter asked, "Have you ever played with a tube like this? Before I drop the ball, let's feel all the bumps on this tube." Both the experimenter and the participant traced the length of the tube with their fingers to "feel the bumps." In the control condition, the experimenter simply began rolling the ball through the tube by saying, "Look at this!"

Next, in all three conditions, the experimenter presented the apparatus without the tubes attached, held the ball above one of the three openings in the lower brace, and asked children to use a small transparent cup to practice predicting where the ball would emerge when dropped. Children were given an opportunity to practice placing the cup under each of the three openings.

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Finally, the experimenter inserted a single tube into the apparatus and dropped the ball through it, allowing children to see that a tube attached to the apparatus constrained the path of the ball. Before dropping the ball, in the imagine condition, the experimenter asked children, “Can you imagine the ball rolling down the tube?” In the wait condition, the experimenter said, “The ball is going to roll down the bumpy tube.” In the control condition, the experimenter called the children's attention to the apparatus by saying, “Look!” Children were given a chance to practice placing the cup where they predicted the ball would emerge once for each of the three configurations shown in Figure 1.

Test trials—Immediately following familiarization, the experimenter fitted all three tubes into the frame. The experimenter held the ball over a predetermined dropping location and repeated the same instructions she gave during the final portion of the familiarization phase (“imagine,” “bumpy,” or “look”), dropping the ball only after children made a prediction and indicated they were ready. After each trial, the experimenter rotated the apparatus 180° to present a novel ball-drop/ball-landing location pairing on the next trial. All children received 12 test trials, blocked into 6 transparent tube trials and 6 opaque tubes trials (counterbalanced for presentation order).

Data Coding

From videotape, for each trial, a primary coder noted whether children placed the cup in the location that would catch the ball (correct prediction), the location directly beneath where the experimenter dropped it (gravity bias error), or the third location (miscellaneous error). The coder also noted the number of switches made before the ball was dropped. To receive credit for a switch, children had to hold the cup under an opening for at least 2 seconds before moving it. For example, if a child initially placed the cup under the right-most opening, moved to the left-most one, then settled on the middle one before indicating that he was ready, then his prediction was coded as the middle opening with 2 switches. Finally, to examine whether the different instructions led to differences in overt problem-solving strategies, the coder scored whether the children traced the tube with their fingers before making a prediction.

A second coder independently scored a third of each participant's trials for reliability. Agreement ranged from 94% – 100% of trials across variables and Kappas ranged from .90 – 1.00. Disagreements were resolved through discussion.

Results

Correct Predictions and Gravity Bias Errors

Inviting 3-year-olds to use visual imagery improved their accuracy on the tubes task, but seeing the ball fall through the transparent tube did not. A 3 (instruction condition: imagine, wait, or control) × 2 (tube transparency order: transparent tube trials first or opaque tube trials first) × 2 (tube transparency color: clear or opaque) repeated measures ANOVA on the number of correct predictions yielded a main effect for instruction only ($F(2, 42) = 6.74$, $p < .01$, $\eta^2 = .24$). We did not find main effects for tube transparency order or tube transparency color, or any significant 2- or 3-way interactions (*p*s > .09). Therefore, subsequent analyses were collapsed across tube transparency order and tube transparency color variables. As Figure 2 shows, and post-hoc Tukey's HSD tests confirmed, children in the imagine condition made significantly more correct predictions ($M = 7.25$, $SD = 3.91$) than the children in the wait condition ($M = 3.00$, $SD = 2.42$; $p < .01$) and marginally more than the children in the control condition ($M = 4.38$, $SD = 4.15$; $p = .07$). Children performed similarly in the wait and control conditions ($p = .52$).

Most incorrect predictions were due to gravity bias errors (87% to 92% of errors across the three conditions). Across the 12 test trials, children in the wait condition made, on average, 7.81 gravity bias errors (*SD* = 2.86); children in the control condition made 6.94 (*SD* = 3.92); and children in the imagine condition made just 4.38 (*SD* = 3.60). A one-way ANOVA on these data yielded a significant effect of instruction condition ($F(2, 46) = 4.20$, $p = .02$, $\eta^2 = .16$). Tukey's HSD tests showed that children in the imagine condition made fewer gravity errors than those in the wait condition ($p = .02$), while children in the control condition did not differ from those in the imagine ($p = .11$) or wait conditions ($p = .76$).

Given a .33 probability of success per trial—there were 3 possible prediction locations—each child was required to make a correct prediction on 8 or more of the 12 test trials to achieve above-chance performance (binomial, $p < .05$). More than half of the children in the imagine condition (9/16) performed above chance, but only 1 and 4 children did so in the wait and control conditions, respectively.

Problem-Solving Strategies

To investigate whether the imagine prompt led children to visualize the trajectory of the ball, we examined how often children made an initial prediction and then made a different prediction before indicating that they were ready for the experimenter to drop the ball. Children in the imagine condition switched on more trials (*M* = 4.38 of 12 trials, *SD* = 1.63) than those in the wait (*M* = 2.88, *SD* = 1.86) or control conditions (*M* = 2.25, *SD* = 1.61). A one-way ANOVA confirmed that the imagine instruction affected the number of trials on which children switched ($F(2, 45) = 6.58$, $p < .01$, $\eta^2 = .23$), and post-hoc Tukey's HSD revealed that children in the imagine condition were more likely to switch than those in the wait or control conditions (*p*s < .05), which did not differ from each other ($p = .56$).

Switching was a good strategy because most switches occurred after an initially incorrect prediction (91%, 83%, and 83% of switch trials for imagine, wait, and control conditions, respectively). Furthermore, as shown in Table 1, the children in the imagine condition were more likely to switch to the correct prediction after an initially incorrect choice (57/128 trials, or 45% of initially incorrect trials) than the children in the wait (26/162, or 16%) and control conditions (25/141, or 18%).

Aside from switching, children did not show other, overt problem-solving strategies. For example, of a total of 576 trials across the three conditions, children used a tracing strategy —trace the path of the tube with a finger before making a prediction—on only 8 trials (1.4% of all trials; on 5, 2, and 1 trials in the imagine, wait, and control conditions, respectively).

Learning Across Trials

To investigate whether children learned from visualizing the solution to this problem, we separated the 12 test trials into two blocks of 6 trials each and examined whether children improved during the second half of the test session (Figure 3). A 3 (instruction condition: imagine, wait, or control) × 2 (trial block: first 6 or last 6 trials) repeated-measures ANOVA revealed main effects for instruction ($F(2, 45) = 5.89$, $p < .01$, $\eta^2 = .21$) and trial block ($F(1, 45) = 7.61$, $p < .01$, $\eta^2 = .12$), and an interaction between the two ($F(2, 45) = 6.67$, $p < .01$, $\eta^2 = .20$). Post-hoc t-tests with Bonferroni corrections confirmed that the interaction resulted from improved performance for the children in the imagine condition only: They responded more accurately on the second block of 6 trials compared to the first block (*M* correct predictions = 4.31 and 2.94, *SD*s = 1.96 and 2.14, respectively; $t(15) = 4.37$, $p < .01$, $d = 67$). Accuracy did not improve between the first and second trial blocks in the wait condition (*M*s = 1.19 and 1.81, *SD*s = 1.11 and 1.64, respectively; $p = .10$) or the control condition (*M*s = 2.38 and 2.00, *SD*s = 2.36 and 2.00, respectively; $p = .30$).

Discussion

We examined whether 3-year-olds' spatial problem-solving abilities can benefit from an invitation to use visual imagery. Children in the imagine condition performed most accurately—they made the most correct predictions, switched more often to correct predictions, and improved across trials. The poor performance of children in the wait and control conditions demonstrated that children in the imagine condition succeeded because of the imagine instructions, not because of the brief delay before children made their prediction or because the experimenter used key words such as "tube" and "roll."

How did a brief invitation to use visual imagery result in significant improvements in children's spatial problem-solving skills? First, it appears that very young children do not spontaneously visualize spatial events when problem-solving; they require an invitation to do so. Nothing prevented children in the wait or control conditions from engaging in imagery on their own, but they apparently did not (see also Dias & Harris, 1988, 1990; Richards & Sanderson, 1999). For young children, then, the first step toward using visual imagery may be an explicit cue to use it.

Second, the imagine instructions may have facilitated problem-solving by leading children to second-guess their initial responses. Participants in the wait and control conditions rarely doubted the accuracy of their predictions. They erred on 66% of all trials (252/384), but switched much less frequently than children in the imagine condition after an initially incorrect prediction (Table 1). Interestingly, the brief delay in the wait condition did not facilitate children's performance, as one might have expected based on the inhibitory control literature (e.g., Diamond et al., 2002;Freeman et al., 2004); instead, an explicit prompt was needed.

Finally, the imagine instructions appear to have provided participants with a mental problem-solving strategy that was more effective than visual feedback. Children who received the transparent tube trials first did not perform better than those who received opaque tube trials first. One might have expected that seeing the ball move through a clear tube would have prompted children to adopt a seemingly straight-forward strategy on subsequent trials: trace visually or with a finger the path of the tube through which a ball is about to be dropped. However, this strategy was almost never used. The absence of overt problem-solving strategies suggests that the improvements in the imagine condition were due to children working out the problem mentally.

It should be noted that despite the clarity of the imagine prompt, we cannot be certain about the actual nature of children's visualization of the falling event. Although young children can understand verbal instructions regarding visual imagery (Dias & Harris, 1988, 1990; Richards & Sanderson, 1999), there are individual differences in children's ability to use visual imagery that last well into late childhood (Estes, 1998; Reiser et al., 1994). Indeed, such developmental differences may explain why only nine children in the imagine condition performed above chance, instead of all sixteen who heard identical imagine instructions. That said, the pattern of errors and switching suggest that the children in the imagine condition did rely on a type of mental operation. When they erred initially by placing the cup in the gravity location, children in the imagine condition were more likely to switch than those in the other conditions, and they tended to switch to the correct location. This strategy suggests that these children placed the cup, then visualized whether the ball actually would wind up there. If not, then they rejected the initial position and moved to the correct location.

In conclusion, we have demonstrated that simply inviting 3-year-olds to use visual imagery can have a remarkable influence on their ability to solve an otherwise difficult spatial problem. Indeed, the imagine instructions allowed them to achieve the level of performance of older children who do not need such instruction to overcome the gravity bias errors (Hood, 1995). It also facilitated performance in an arguably more indirect way than other studies that gave explicit verbal information about the movement of the ball through the tube (Bascandziev & Harris, 2009) or the location of the ball after it comes out of the tube (Jaswal, under review). These results suggest that at least by 3 years, children possess the prerequisite skills required to overcome the gravity bias, but have difficulty deploying those skills spontaneously. Children who are on the cusp of being able to solve a problem may benefit from being encouraged to use their imagination.

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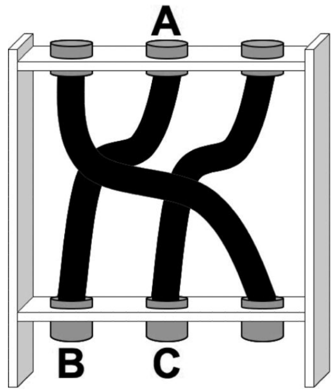

Figure 1.
Test apparatus: Three tubes were fitted into the top and bottom brace of the apparatus in an intertwined fashion, preventing a ball dropped down any tube to fall straight down. For example, if the ball was dropped into the opening labeled A, then the correct prediction would be location B. Predicting at location C reflected a gravity bias, i.e., expecting the ball to fall down vertically regardless of the path created by the connected tube.

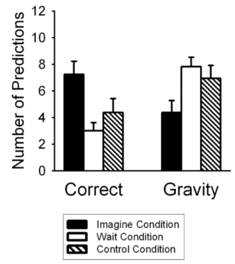

Figure 2.
Mean number of correct predictions and gravity bias errors for the three instruction conditions. The error bars denote mean standard error.

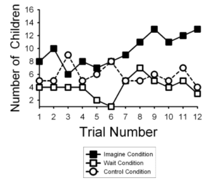

Figure 3.
The number of children who made a correct prediction on each test trial in the three instruction conditions.

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Table 1

The number of trials in which children switched or did not switch after an initially incorrect choice, and the number of trials in which switching led to a correct prediction.

	Imagine	Wait	Control
Initially correct	64	30	51
Initially incorrect	128	162	141
No switch	64	124	111
Switch	64	38	30
Switch to incorrect	7	12	5
Switch to correct	57	26	25
Total correct	121	56	76

Note: Each instruction group received a total of 192 test trials (16 participants, 12 trials per participant).