

Gravity Rules for 2- to 4-Year Olds?

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2- to 4 $\frac{1}{2}$ -year-olds were tested on an invisible displacement task in which the goal was to find a toy ball that was dropped down one of potentially three opaque tubes that could be interwoven to produce a visuospatial maze. Performance on the task was significantly related to the number of tubes with older children solving configurations with more tubes than younger children. When transparent tubes were used, children found the ball but this success did not transfer back to opaque trials. In addition to the relation between performance on the task and age, a significant phenomenon was discovered in that errors were consistently directed to the location directly below the last seen position of the ball. The developmental trend may reflect both a partial understanding of the contingency between tubes and hiding locations as well as an increase in the ability to overcome the prepotent response to search in the gravity/aligned location.

The studies reported in this article developed out of two different developmental issues. Initially, the plan was to develop a new measure of spatial reasoning for preschool children that did not involve fine motor skill. This was to be achieved by using a novel invisible-displacement task involving the force of gravity. However, this task revealed the second developmental issue, namely, preschool children's reasoning about invisible displacements caused by gravity.

By 4 to 5 years of age, most children demonstrate considerable mastery of their spatial world but comparatively little work has been conducted on the development of spatial skills during the 2- to 4-year-old period. One area that has been successful in charting the development of a particular type of spatial skill during this period is the block-construction task. In an analysis of spontaneous play with toy wooden blocks, Stiles-Davis (1988) demon-

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strated that there was a developmental trend with children of increasing age producing more advanced constructions made up of more complex spatial arrangements of the blocks than at earlier ages. However, performance on block-construction tasks in younger children may be dependent on factors other than spatial skills, such as motor ability which also undergoes change over the same period. In addition, advanced constructions, such as arches, also require forward planning. With these factors in mind, Hood (1993) developed a new test of spatial reasoning that was believed to reduce the effect of these additional factors. This was achieved by requiring a minimum, simple, declarative gesture to one of three potential hiding boxes that was the location of an invisibly displaced ball.

By the end of the 2nd year of life, children understand that objects can exist and move independently to locations that can not be directly perceived (Piaget, 1954). An illustration of this understanding is the invisible displacement problem in which an object is concealed within a container and moved to a number of potential hiding places by the experimenter. At some point in the sequence, the experimenter surreptitiously deposits the object at one of the locations but the child is only shown the empty container at the end of the sequence. By 2 years of age, most children recognize that the object continues to exist and that it can be found at one of the locations. However, as Sophian (1986) pointed out, this does not prove that the child has reconstructed the movement of object; rather, it only proves that it continues to exist at one of the locations that would be revealed by any search pattern. As the hiding event is invisible, every location is potentially valid. To address this issue, Sophian (1986) used the spatial-transposition problem in which an object is hidden in one of three containers and then that container and one other are interposed. Although the displacement is invisible as in the Piagetian sequence, the correct location in the spatial-transposition task is unambiguously specified by the location of the correct container and the child must track the invisible movement to solve the task.

However, there are potential problems for both the invisible displacement and the spatial-transposition task arising from the fact they are produced by an adult human agent. Young children may perform poorly because of the unfamiliar interaction with a stranger. In addition, hide-and-seek games between adults and children frequently involve some form of deception as demonstrated in the traditional Piagetian task in which the toy is secretly deposited and so children may not use logical search patterns because they believe that there is some form of trick taking place. An adult analogy of these sorts of tasks is the shell game in which one has to monitor the invisible displacement of a concealed object. One way to overcome this potential problem is to avoid human agents and use displacements caused by physics. Secondly, invisible displacements produced by human agents represent only a proportion of those events that occur naturally. Inanimate

objects can move independently and invisibly to a new spatial location if certain forces act on them. One such force is gravity that acts on unsupported bodies to propel them in a straight-down trajectory unless some obstacle halts or diverts the path of the object. There may also be a distinction between the way children reason about displacements implemented by a person compared to those caused by physics.

Recent studies by Spelke and her colleagues (Spelke, Breinlinger, Macomber, & Jacobson, 1992) demonstrated that 4-month-old infants, who are too young to search manually, understand that unsupported bodies fall in a straight line unless an obstacle impedes trajectory. Therefore, older children who can competently search for hidden objects should solve invisible displacements involving the force of gravity. Furthermore, these children should also understand the way that solidity constrains the movement of a traveling object and predict the trajectory of an invisibly displaced ball that moves through a confined space, such as a tube. Together, the use of gravity and tubes that redirect the movement of an object to a new spatial location formed the basis of a new task (Hood, 1993). Spatial skill was to be assessed by producing invisible displacements of greater complexity by forcing the object to move in a more elaborate trajectory.

The goal of the task is to find a rubber ball that is dropped down an opaque plastic tube that feeds into one of three potential hiding places. The task resembles an interactive version of the visual maze or tangled strings problem in which the objective is to trace a trajectory through the perceptual interference of distracter paths. Like the paper-and-pencil games, it was believed that task difficulty would be determined by the degree of perceptual interference produced by crossover trajectories, as well as the complexity of the invisible displacement. The advantage of this apparatus is that the motor response is independent of task difficulty, with the child simply pointing or touching one of the containers. In comparison to construction tasks, there would also be very little means-end planning.

As shown in Figure 1, the original apparatus was constructed to assess spatial skills by examining search in arrangements of increasing complexity of the three intertwined tubes. However, during pilot work, it became apparent that children below 4 years of age found this task extremely difficult. Two-year-olds would reliably search for balls in containers when they were connected to the chimney by a single vertical piece of tube. Therefore, the youngest children understood the vertical invisible displacement produced by gravity.

However, when the trajectory was nonvertical as in a chimney connected to a nonaligned container (see Level I of Figure 2), children made errors. By increasing the number of tubes and potential hiding locations, search errors could be increased that appeared to be linked to age. Three levels of task difficulty were considered and are shown in Figure 2. This was supported by

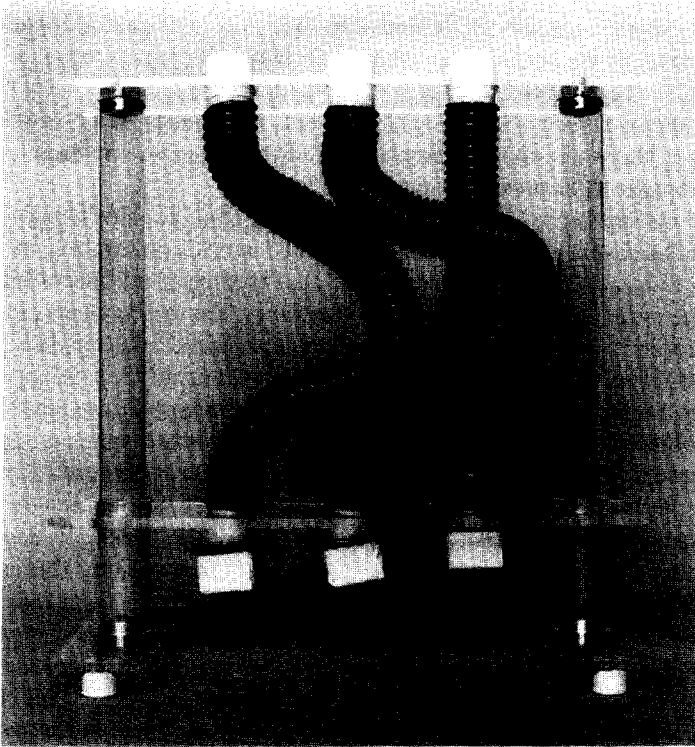
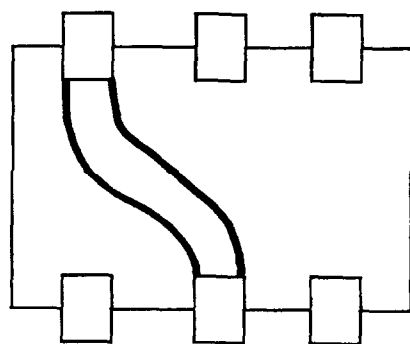


Figure 1. Photograph of the tubes apparatus configured for Level III.

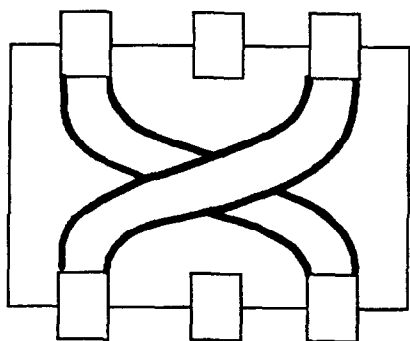
the finding in pilot work that no child demonstrated the ability to solve harder levels before solving easier levels of the task. Furthermore, children passing at lower levels who then made errors at the higher levels would go on to pass at the lower levels, indicating that the failure was not attributable to boredom. These initial observations suggested that the tubes task had levels of difficulty associated with age.

EXPERIMENT 1

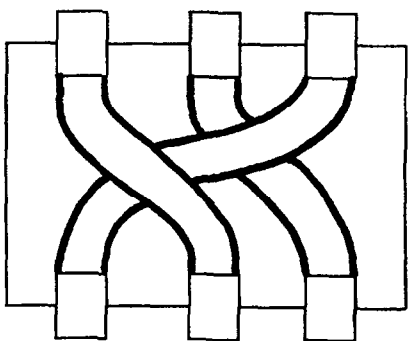
As this was a new task, the first aim of the study was to establish at what age children could solve the three hypothetical levels of difficulty. Given that we did not know the relation between age and performance, an unusual experimental design was employed in which the dependent variable was the age of each child and the independent variable was the level at which they no longer significantly found the ball. Each child began at the "easiest" level of the task and progressed to further levels of difficulty if they passed the correct search criterion.



Level I



Level II



Level III

Figure 2. Three levels of difficulty of the tubes task.

Method

Participants. A normally distributed sample of 209 children ranging in age from 19 to 37 months participated in Experiment 1. This group was comprised of 90 female children with a mean age of 36.8 months ($SD = 8.2$) and 119 male children with a mean age of 37 months ($SD = 8.3$). They were tested individually either at local nursery schools or in the developmental laboratory by four different experimenters. The younger children tended to be recruited as siblings of infants attending a clinic for visual screening, whereas the other children were tested in local schools. Three 2 year olds did not begin testing because of mood. The drop-out rate was extremely low, partly due to the minimal number of five trials as the criterion to be included in the study as well as the fact that the task was perceived as a game and engaged the children.

Apparatus. The apparatus was made out of transparent Plexiglass and consisted of a frame with three opaque chimneys on the top section and three opaque containers directly below. The chimneys and containers were connected by opaque, plastic tubing. The horizontal separation between the containers was 13 cm and the vertical distance between the chimneys and containers was 40 cm. The tubes were made of gray, flexible plastic that was ribbed for rigidity. The diameter of the tubes, chimneys, and container sections was approximately 5 cm and the connections were maintained by friction. The hiding boxes were $6 \times 6 \times 4$ cm, had a circular hole in the top, and were also held in place by friction. The colored balls (blue, red, green, pink, purple, and yellow) were 3 cm in diameter and were made of light-weight rubber spikes. The movement of the balls within the tubes was deemed to be inaudible by adult observers.

Procedure. Testing took place in quiet locations with the apparatus, child, and experimenter seated on the floor. Prior to testing, the child was familiarized with the different pieces of apparatus in the following way. The child was given one end of the tube to hold and the experimenter dropped the ball down the tube that was inclined at approximately 45° . This was repeated three times. The purpose of this was to ensure that the child had been shown that the opaque tube was hollow. The experimenter then removed the tube and presented the Plexiglass frame. The hiding boxes were then attached to the frame and a ball was placed directly in one of the boxes. The child was then asked to locate this ball. Children varied in their search behavior in that most would pull off the box but some would simply point and expect the experimenter to remove the box. The experimenter then demonstrated the hiding retrieval sequence by connecting a chimney to a nonaligned container with one length of tube, dropping the ball down the

chimney, and then pulling off the correct container to show the child the location of the ball. The child was never shown a vertical tube arrangement.

At this point, the formal test began. In between every trial, the experimenter changed the configuration of the tube or tubes according to a schedule sheet that illustrated every possible spatial configuration at each level. The purpose of this was to ensure that the child had to reevaluate the change of spatial layout on each trial. This was either achieved by the experimenter reconnecting tubes or by reversing the apparatus that produces a mirror image of the previous configuration.

Children varied in their behavior with regards to dropping the ball down the chimney; therefore, a flexible procedure was used by the experimenter in order to adapt to the individual child. Some children insisted on performing the act and would become distressed if attempts were made to retrieve the ball, whereas others preferred to allow the experimenter to drop the ball. Most children fluctuated between these two extremes during the testing sessions as the "game" progressed. There was no evidence that these different behaviors produced different performance. Once the ball had been dropped down the chimney, it was out of sight until it was recovered. The journey of the ball took just over 1 s. Following the drop, children also varied in their behavior; most immediately began searching, whereas others would hesitate momentarily before making a decision. Again, there was no evidence that these different behaviors reflected in different performance.

Children searched until they found the ball and pattern of search behavior was recorded on a score sheet by the experimenter. However, the order in which children solved the task (e.g., correct on first three trials) was not recorded as it was not anticipated that this factor would be important (see Experiment 4 for a rectification of this situation). Each child began on Level I and was tested with five trials. If they found the ball correctly on four out of five trials ($p < .05$, three-choice binomial distribution), they progressed to the next level in which five trials were again administered. The level at which they no longer significantly found the ball was taken as their performance level.

Results

Performance level was the independent variable and age was the dependent variable. An analysis of variance revealed a significant effect of performance level, $F(3, 205) = 43.1, p < .001$ (see Figure 3). As expected, higher levels of performance were attained by older children. Post hoc analysis with the Scheffé test revealed that all groups were significantly different from each other in age apart from children who failed at Level III and those who passed Level III. It is worth noting that if the age range had extended to older children then a significant difference would emerge between these two groups as the mean for passing Level III would shift further away from

Age Differences Related to Performance

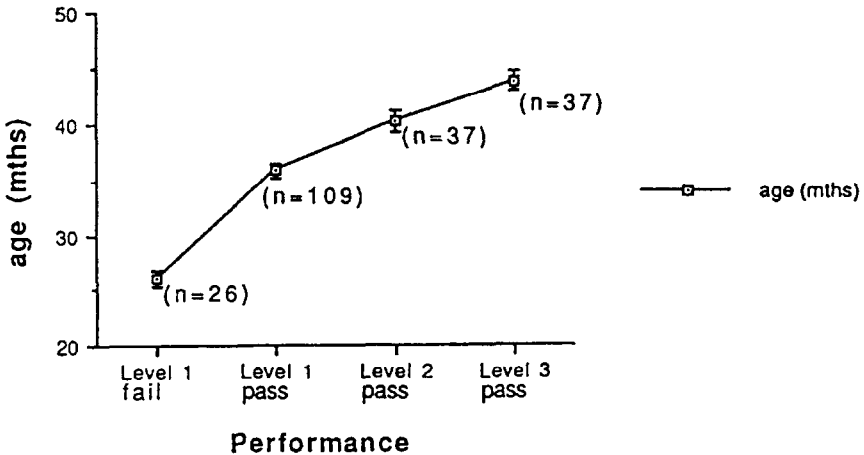


Figure 3. Relation between performance and mean age in months with standard error bars. Children were judged to have passed a level if they found the ball correctly on their first search attempt on at least four out of five trials.

the mean of failing Level III. An analysis of covariance of performance by gender, covarying with age, revealed a significant main effect of gender, $F(3, 205) = 6.1, p < .02$, with boys obtaining better performance scores than girls.

A breakdown of scores at each level revealed that performance was particularly poor in children who failed Level I. Out of five trials, 14 children (54%) scored no correct searches, 4 (15%) scored one, 5 (19%) scored two, and 3 (12%) scored three. Of children who failed Level II, 33 (30%) scored no correct searches, 30 (28%) scored one, 25 (23%) scored two, and 21 (19%) scored three out of five trials. In children who failed Level III, 4 (11%) scored no correct searches, 7 (19%) scored one, 12 (32%) scored two, and 14 (38%) scored three out of five trials.

When it became apparent that errors may not be randomly distributed, search patterns for the last 140 children included in the study were recorded. These were analyzed in terms of the first and second locations at which they searched during incorrect trials. If children failed on the first and second search, they usually found the ball on the third attempt but on some occasions they would repeat errors if the box had been reconnected to the apparatus. As predicted, this analysis revealed that search

errors were not randomly distributed between the two incorrect locations. At Level I, 36 search patterns were available for analysis. Thirty out of 36 first searches (83% of errors) were directed to the box directly below the chimney. This error is significantly above chance ($p < .05$, binomial distribution) and is referred to as the gravity error. However, 19 out of 36 second searches (53%) were successful which is equal to chance (with only two remaining boxes, the child has a 50% probability of being correct).

At Level II, 166 out of 227 incorrect first searches (73%; $p < .05$) were gravity errors. The reason for a lower percentage of gravity errors at this level is that children in this group seldom searched below the box if it was not connected by a tube. This is supported by the finding that 180 out of 225 second searches (80%; $p < .05$) were correct at this level. Two examples of these configurations are shown in Figure 4. On average, these configurations represented 25% of test trials and gravity errors occurred on 15% of these trials. Therefore, if only trials with a box connected below are considered, then 93% of first searches were gravity errors. A similar proportion of gravity errors appeared at Level III with 89 out of 97 first searches (92%; $p < .05$) producing gravity errors, whereas 48 out of 95 second searches were not significantly above chance at 51%.

Discussion

As predicted from the pilot studies, there was a strong relation between task performance and age with older children solving more complicated levels of the tubes task. The gender difference is also consistent with other studies of spatial reasoning (for a review, see Halpern, 1992). However, it is unlikely that the tubes task is addressing a pure spatial problem. It would appear that children who failed on these different levels were not using the tubes to direct their search behavior. Initially, all search was predominantly determined by the straight-down trajectory, irrespective of the tube. Older children passed this first level, but this appeared to be achieved by learning the rule to search at a hiding location that had a tube connected. Therefore, gravity errors did not tend to occur in Level II at vertical boxes that were not connected with a tube. This interpretation is also supported by the finding that second searches are significantly above chance. The increase in straight-down errors on first searches in Level III and the fall-to-chance performance on the second search is also consistent with this interpretation as all containers were connected and so the Level II rule no longer applied. Spatial strategies may begin to appear around Level III where children must use the shape of the tubes to solve the puzzle.

In relation to search on Piagetian invisible-displacement tasks, performance on the tubes task was much worse than expected, even at the youngest age studied. Over 50% of children who failed at Level I on the task were

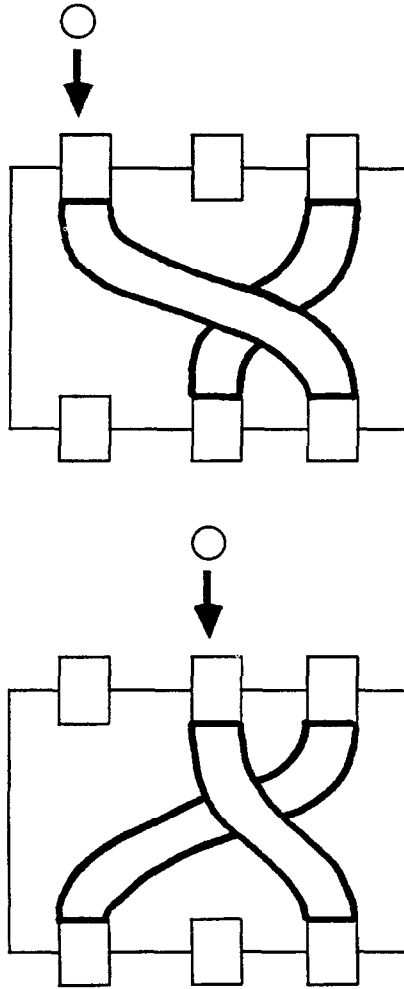


Figure 4. Two examples of Level-II configurations that did not produce gravity errors when the ball was dropped down the tube indicated by the arrow.

unable to find the ball at all on five trials. Not only does this indicate that no learning is taking place, but also that children are performing worse than could be expected using a random strategy. Clearly, not all invisible displacements are equivalent.

In the tubes task, the children have to infer the trajectory of the ball from the shape of the opaque tube. Two additional studies were conducted using transparent tubes to determine whether visible displacements would improve performance on the same apparatus.

EXPERIMENT 2

The purpose of this experiment was to determine whether performance would be improved by allowing the children to see the movement of the ball. This was tested in 15 children below the age of 3 years old, using the same procedure but substituting transparent tubes for opaque ones. On the basis of the data from Experiment 1, the performance of the majority of children of this age with opaque tubes would be expected to fall between failing at Level I and passing Level I (see Figure 3). If visibility is the important factor, then this age group should pass more difficult levels.

Method

Participants. Eight female children with a mean age of 32.12 months ($SD = 5.52$) and 7 male children with a mean age of 34.29 months ($SD = 3.1$) who had not participated in Experiment 1 were tested in this part of the study. Experiment 2 was conducted in a laboratory setting and tested by one experimenter.

Apparatus. The apparatus was identical to that used in Experiment 1 except that transparent tubes were substituted for opaque ones. The plastic was not fully transparent but was sufficiently translucent to see the movement of the darker colored balls.

Procedure. The procedure was identical to Experiment 1, except that in the pretesting phase the child had to point to the ball and track its movements inside the tube that was held horizontally in front of the child by the experimenter. This was to ensure that the child could see the movement of the ball.

Results

Twelve children passed Level III, 1 child passed Level II, and 2 children passed Level I. The small number of errors made by these children were in the gravity-defined location. No child failed at Level I, indicating that performance was substantially better when children could track the movement of the ball.

Discussion

When they could see the movement of the ball through the tube, children found the ball at the most difficult level of the task. This indicates that the poorer performance by this age group in Experiment 1 is not attributable to inappropriate motor demands or fatigue. Although some children did not reach Level III, this may be because the additional tubes obscured the

visibility of the movement of the ball that was fairly rapid and so a lapse in attention would have produced errors.

EXPERIMENT 3

Experiment 2 demonstrated that young children, who were recruited specifically to investigate the role of visibility in the task in the laboratory setting, could perform substantially better on the tubes task when they could see the movement of the ball. The next question to address was whether the experience from the transparent testing would transfer to the opaque conditions. In order to establish a learning effect, children failing at one level had to show an improvement following training with the transparent tubes. Therefore, a subgroup of children who formed part of the larger group of Experiment 1 were also tested with the transparent tubes. These children were selected on the basis of failing at Level II. The same rationale would also apply to Level I and Level III and both could have been used for this experiment, but Level II children were chosen because they were more numerous.

Method

Participants. Seven female children with a mean age of 35.86 months ($SD = 5.58$) and 9 male children with a mean age of 33.22 months ($SD = 6.06$) who failed at Level II in Experiment 1 were tested in Experiment 3. These experiments were run concurrently by three experimenters in the local schools.

Apparatus. The materials were the same as those used in Experiments 1 and 2.

Procedure. After testing with the opaque tubes, the children were immediately tested with an additional five trials using the transparent tubes at the same level. Children who did not pass Level II with the transparent tubes were not tested as they did not show any learning, but those who passed this level were tested again in the opaque condition with five trials at Level II.

Results

Fifteen out of 16 children passed Level II when transparent tubes were used. These children were immediately retested at Level II with opaque tubes. Only 2 children out of these 15 ($p < .05$, binomial test) subsequently passed this level indicating that there was no evidence for a significant transfer during the opaque-transparent-opaque sequence. In the first opaque test,

82% of errors were gravity errors compared with 79% in the second opaque testing condition.

Discussion

The results from Experiment 3 support Experiment 2 in that most children (15 out of 16) improved on this task when they could see the movement of the ball. However, there was no evidence for significant transfer of this experience when they were tested again with the opaque condition. In addition, this group not only had the opportunity to improve with transparent training, but also with repeated exposure. This suggests that performance limitations on the task are a robust finding that does not easily extinguish following a period of training or repeated exposure.

EXPERIMENT 4

An analysis of search patterns in Experiment 1 indicated that performance at Level I of the task was particularly poor with over 50% of children scoring no correct searches out of 5 trials. Experiment 3 demonstrated that training with transparent tubes did not facilitate performance for children at Level II. One explanation for this poor performance is that search behavior is dominated by the initial gravity error when the child cannot track the movement of the ball. However, it is not clear why performance is so poor. The tubes task may be particularly difficult because the continually changing arrangement of the chimneys and correct hiding boxes simply confuses the children so that they choose the default search option that is to search directly below. Another possibility may be that children are simply unfamiliar with the apparatus so that they do not understand the mechanism of the tube. Children typically perform better on a number of object-related tasks when they are accustomed to the objects. The familiarization with the tubes prior to testing in Experiment 1 may have been insufficient to teach the children the mechanism, especially as it only takes two errors to falter at any level.

The purpose of Experiment 4 was to address these issues by training the youngest children to solve the task at Level I. Above this level, there is evidence that children understand some aspects of the tube mechanism as indicated by second searches in Experiment 1. Training consisted of pretesting the children with the same arrangement repeatedly until they correctly solved the task on five consecutive trials. This repeated testing should provide an estimate of the strength of the search bias by determining the number of trials it takes children to learn the correct response. This would also provide information about the pattern of search behavior on a trial-to-trial basis that was not recorded in Experiment 1. After training, the critical question to address was whether or not children who had learned the

correct response during the pretest trials understood the tube mechanism. This was investigated on one test trial using a new configuration.

Method

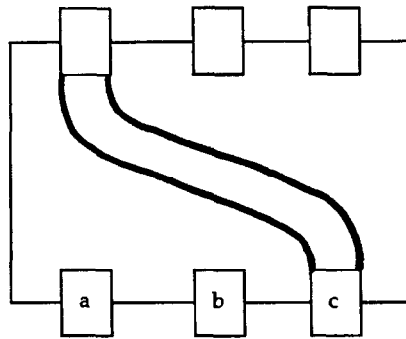
Participants. Four female children with a mean age of 27.2 months ($SD = 1.5$) and 6 male children with a mean age of 27.8 months ($SD = 1.1$) who had never been tested with the tubes apparatus were recruited for this study. This age was chosen as these children were most likely to fail at Level I of the task.

Apparatus. The materials were the same as those used in Experiments 1 and 2. A toddler chair located 3 ft from the tubes apparatus was used for seating the children.

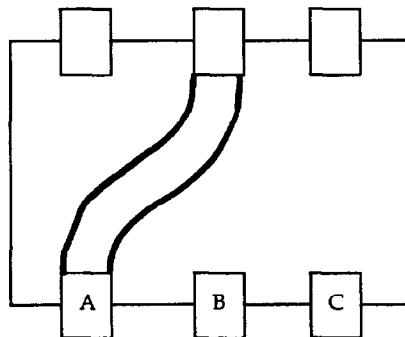
Procedure. Children were familiarized with the apparatus as in Experiment 1. However, this time children were tested with the tube arrangement shown in Figure 5 repeatedly until they scored five correct initial searches consecutively. Half of the children were tested with the mirror image of the arrangement in Figure 5 to counterbalance direction of responses. All responses were video taped. In order to standardize the testing procedure for each participant, the child was required to sit on a toddler chair next to the parent prior to each hiding event. An experimenter dropped the ball and then asked the child to approach the apparatus and find the ball. The time interval between dropping the ball and searching by the child at the first location was typically around 4 s. After five consecutive correct responses, the tube arrangement was changed to the arrangement shown in Figure 5 and one test trial was administered.

Results

The individual search patterns of each child are shown in Table 1. Lowercase letters (*a, b, c*) indicate pretest locations, whereas uppercase letters (*A, B, C*) represent test locations. The trial by trial analysis reveals a degree of variation between children when tested with the repeated paradigm. For example, Participant SL did not make an initial correct search even after 22 trials, whereas Participant TS only made an initial error on the first pretest trial. Nine children achieved the test criterion of five correct initial searches. Due to experimenter error in counting trials on line, Participant FE was overexposed on the pretest phase and should have been given a test at Trial 11. Apart from Participant TS, who only made one pretest error, all of these children to a lesser or greater extent progressed through a transitory stage of missing out the middle box on their second search attempt before attaining the pretest criterion. Participant WS underwent a stage of grasping the



PRE-TEST



TEST

Figure 5. Configurations used for Experiment 4. Children were tested with the first configuration (or its mirror image) until they found the ball correctly on five consecutive trials. They were then tested with the test configuration (or its mirror image). Locations in the pretest trials are referred to in the text in the lowercase, whereas the same locations in the test trials are referred to in the uppercase.

box at Position a before correcting himself and searching at Position c. On the test trial, only one out of the nine (Participant RJ) correctly searched on the first attempt, indicating that most children did not learn the mechanism ($p < .05$, binomial distribution). Of these eight children who failed on the test trial, three searched in the previously correct box at Position C, including Participant FE who had been overexposed to Location c on the pretest phase. However, five children searched at Position B which had not been reinforced. Four children were correct on their second search attempt, two

Table 1. Individual Search Patterns for Experiment 4

Participant	FE	TS	RJ	CA	HS	NT	WS	RA	BM	SL
Trial 1	abc	abac	abc	abc	abc	abc	bac	abc	ac	abc
Trial 2	ac	c	abc	abac	abc	c	abc	ac	abc	abc
Trial 3	ac	c	ac	abc	abc	ac	abc	ac	ac	abc
Trial 4	ac	c	c	abc	abc	bc	a → c	abc	c	abc
Trial 5	ac	c	c	aabc	abc	abc	a → c	ac	ac	abc
Trial 6	c	c	c	ac	abc	abc	c	c	ac	abc
Trial 7	c	Test: BA	c	ac	abc	abc	a → c	ac	ac	abc
Trial 8	c	c	c	ac	ac	ac	c	ac	c	abc
Trial 9	c		Test: A	c	ac	ac	Test: BCA	ac	ac	abc
Trial 10	c			c	ac	ac		abc	ac	abc
Trial 11	abc			c	ac	ac		ac	c	abc
Trial 12	c			c	c	ac		ac	c	abc
Trial 13	c			c	c	c		c	c	abc
Trial 14	c			Test: BCA	c	c		c	c	abc
Trial 15	c				c	c		c	c	abc
Trial 16	c				c	c		c	Test: CN	abc
Trial 17	Test: CA				Test: BA	c		c		abc
Trial 18					Test: BN	c		Test: CA		abc
Trial 19										abc
Trial 20										abc
Trial 21										abc
Trial 22										abc; N

Note. For the pretest phase, a = gravity box, b = nongravity box, c = correct box, n = no search, and a → c = touches a but then c. For the test phase, A = correct box, B = gravity box, C = nongravity box (pretest c), N = no search.

were correct on the third search, and two children abandoned their search after the initial failure.

Discussion

The extensive training provided in Experiment 4 produced no evidence that children could learn the tube mechanism as a significant proportion failed to pass the test condition when the tube arrangement was changed. This was not solely attributable to perseverative errors as children tended to search first at Position B rather than Position C on the test trial. This finding is particularly surprising as search at Position c was reinforced during the pretest phase, whereas search at Position b was never reinforced. Position B was only appropriate in terms of the prepotent gravity error.

The fact that most children underwent a transitory stage during the pretest phase of searching at Position a, missing out Position b, and then searching at the correct Position c also suggests that children at this point in the testing procedure were beginning to appreciate something about the true location of the ball but that search at Position a was still the predominant response. No child underwent a stage where search at Position a dropped out before search at Position b. This indicates that successful search at Position c occurs after and only after search at Position a has been eliminated. How can this change in the pattern of search behavior during the pretest phase be best understood? One useful way is to consider the order of search as a reflection of the strength of the response to search at a location irrespective of the tube. For example, most children began with the pattern Position a followed by Position b, and then by Position c. In terms of search strength, this can be regarded as Position a is greater than Position b and Position b is greater than Position c. This is a plausible search strategy for a fallen object as adjacent spatial locations have a high probability of being the correct resting location. However, in the children who reached the correct search criterion, the pattern tended to change to Position a followed by Position c or Position a is greater than Position c and Position c is greater than Position b. As Position c was the correct solution, there was no need to search at Position b. This suggests that Position b dropped in relative strength to Position c as search at the correct location became reinforced. At this point, there is evidence that search is no longer random and there is some knowledge of the location of the ball. Finally, search at Position c becomes the first response so that Position c is greater than Position a and Position a is greater than Position b. However, this pattern does not determine whether the response to location Position a has been inhibited or alternatively, search at Position c has increased in relative response strength to Position a so that it becomes the dominant response. Finally, in the test phase, the finding that Position C is not the most common error in the test

condition indicates that failure on the task is not because children persevere to the last correct location.

GENERAL DISCUSSION

In the course of developing an interactive spatial reasoning task that is not dependent on motor or planning skills, a perseverative search error has been identified. Although the tubes apparatus allows for a manipulation of spatial complexity by increasing the number of tubes and crossover points, children below 4 years of age do not consistently use this information when directing their search. Therefore, the developmental change demonstrated in this task is unlikely to be solely attributable to an increase in spatial skills. Rather, an analysis of the search errors reveals that children may undergo a progressive understanding of the way tubes constrain the movement of a falling object. These findings raise two important questions. What changes allow children to solve more complex versions of the task and why do errors tend to occur at the same location? As reviewers have pointed out, the harder levels of the task may simply be more confusing and there are a number of potential manipulations that would be expected to improve performance, such as not crossing the tubes or using tubes of different colors. All of these manipulations would aid the child by reducing visual distraction and drawing the child's attention to the relevant aspects of the task. There are a number of mundane explanations that could account for the age trend on the tubes task, such as an increase in memory capacity or information-processing abilities, but if this was all that the task demonstrated, then it does not contribute significantly to the general finding that older children can perform more complex tasks than younger children. However, the pattern of search behavior reveals an interesting phenomenon with regards to the way children infer the trajectory of an invisibly falling object.

Initially, 2-year-old children do not understand the mechanism of the tube and how it constrains movement. However, over the next year, there appears to be a progressive understanding of the mechanism operating in the tubes task. As children failing Level I do not understand the mechanism, they assume that all falling bodies travel in a straight line that conforms with their previous experience. Children who reach Level II may begin to have a rudimentary understanding of the apparatus as they tend not to search at locations that are not connected by a tube. This suggests that they appreciate some role of the tube. The errors found at Level II may reflect a transitional period in which the mechanism information is beginning to constrain inferences about where the ball could be. Level III is more difficult than Level II because there are three connected boxes and spatial skills may begin to operate as children now have to use the shape of the tube to identify the correct hiding location.

However, in addition to acquiring the tube mechanism, the change in performance may also be attributable to a corresponding reduction in perseverative search strategies that appear to dominate the younger children's behavior. Across all levels, errors occur significantly at the box directly below the last seen position of the ball. This indicates that there is a predominant response to search for an invisibly displaced, falling ball directly below. This was particularly striking in Experiment 4 in which individual search patterns revealed surprisingly robust perseveration in the youngest children despite intensive training. Unlike other examples of perseverative search errors, such as the A and not B error, there is no reinforcement schedule during the testing that could account for this behavior. There are a number of possible ways of describing this error, such as searching in the closest location to the proximity of the last seen position of the ball, the aligned location within the frame of the apparatus, or the place specified by the vertical gravitational line if the tubes did not exist. Further experiments are required to determine which of these alternatives are correct but for this article, the gravity error seems a reasonable label for this phenomenon.

The origin of such an error can be traced to around 6 to 7 months of age, when Piaget (1954) described a transition from a situation in which the infant continues to look at the hand once an object has just been released, to one in which the infant begins to anticipate the object by immediately looking at the ground below. Given that on most occasions this strategy will be successful, it may become predominant through reinforcement and interfere with the acquisition of new knowledge, such as how the mechanism of a tube works. Diamond (1991) noted that "cognitive development can be conceived of, not only a progressive *acquisition* of knowledge, but also as the enhanced *inhibition* of reactions that get in the way of demonstrating knowledge that is already present" (p. 67). Cognitive development must involve the ability to predict outcomes in the world as well as adjust those predictions when they fail. When the child cannot see the movement of a falling object, he or she predicts that it will travel straight down, even though he or she does not find it there on repeated trials. In the transparent tube version, there is no need to predict the location as the movement of the ball within the tubes draws the child to the correct box.

One hallmark of inhibitory failures is that participants should be capable of performing the correct response when the prepotent response is removed. In other words, there is a correct response that the participant cannot execute because the prepotent response dominates behavior. Therefore, after searching at the location directly below on the first search, children should correctly search on the second attempt as the prepotent option has now been removed. In Experiment 1, Level-II children did make correct second attempts which indicates that they knew something about where the

ball could be. However, Level-I and Level-III children searched randomly on their second attempt suggesting that there was no knowledge of the location of the ball. However, Level-I children in Experiment 4 underwent a period of search behavior that suggested that they could learn something about where the ball was and that this occurred after and only after the response to the gravity location had been eliminated. It should be noted that at this point, the behavior did conform to the inhibitory failure definition in that after they had made the prepotent response, children made the correct response. When they finally reached the point of solving the task consistently, it is not clear whether this was achieved by inhibiting search at the gravity location or rather search at the correct location had been simply reinforced to a level in which it became the predominant response.

One potential problem with the inhibitory account is that children do not make errors when they can see the movement of the ball through the transparent tube into the hiding box. As one reviewer pointed out, an inhibitory account would predict that once the ball had become invisible again, the child should return to making a gravity response. However, it does not follow that the child should now make a gravity error, as children of this age are capable of remembering the last seen position of the ball. There is no need to infer a trajectory so the child simply searches where he or she saw the ball go. Furthermore, if the child did make a gravity error with transparent tubes, as some did, then one could not conclude that this was an inhibitory failure either as the child may simply have lost track of the ball.

The gravity error is consistent with studies examining the development of beliefs about falling objects in which it was shown that preschool children initially formulate an omnibus prediction that all unsupported bodies fall in a straight line (Kaiser, McCloskey, & Proffitt, 1986; Kaiser, Proffitt, & McCloskey, 1985). This was demonstrated by asking the children to predict the trajectory of a falling object under a number of different circumstances, such as rolling off the edge of a table or being dropped by a flying plane. Irrespective of the magnitude of the horizontal component determined by the velocity of the forward movement, preschool children rarely chose the correct parabolic trajectory but instead predicted a vertical drop. However, unlike the studies by Kaiser et al. (1986) and Kaiser et al. (1985) in which the first answer is taken, the children in the tubes task have a number of opportunities with feedback to solve the task. Nevertheless, children below 3 to 4 years of age appear to ignore this information when they are searching.

So far, the tubes task has been used to examine vertical invisible displacement and the error has been attributed to a prepotent gravity rule, but there is evidence that the error also emerges in horizontal invisible displacements. In their study of contingency learning, Zelazo and Frye (1993) presented 3 to 5 year olds with a horizontal marble runway board (slightly inclined) that

had two straight pathways and two pathways that crossed over in an "X" pattern. They trained the children that an on light indicated that the ball would travel across to the opposite side and an off light indicated that the ball would travel straight down and appear at the same side at the bottom of the ramp. This contingency was explained to the children on the unoccluded apparatus and the lever mechanism that determined the trajectory was demonstrated. The pathways were then occluded by placing a board over the top and children were asked to predict where the marble should end up on the basis of the light. Irrespective of whether the light was on or off, 3-year-old children would chose the straight horizontal trajectory rather than the one that crossed over, whereas 4- and 5-year-olds could predict the appropriate trajectory. Zelazo and Frye interpreted their findings as an inability of preschoolers to switch between different rules but the predominance of the straight pathway is also consistent with predominant response biases guided by naïve theories of physics. Taken together with the present findings, this suggests that below 4 years of age, children infer that invisibly displaced objects move in a straight line either vertically or horizontally but not diagonally.

If the phenomenon observed in my study is attributable to a naïve theory of gravity, then future studies should investigate whether children predict straight trajectories that do not obey the laws of gravity. For example, if the balls could travel upward against gravity, then errors would suggest an alignment account. On the other hand, as antigravity trajectories are relatively rare in comparison to gravity events, an absence of errors would support the suggestion that experience with falling objects has predisposed young children to make naïve inferences in the current set of studies. Further studies must also address whether the errors reflect an inhibitory failure rather than a limited understanding of the tube mechanism. Although the transitional stage observed in Experiment 4 when training the children to pass the task is suggestive of an inhibitory mechanism, the data is still not conclusive. As noted earlier, one possibility is that the error represents both an initial misunderstanding of the tube mechanism but also a failure to learn the mechanism because of competing dominant theories. The process of adjusting behavior in light of new evidence may involve the process of inhibiting former theories that guide that behavior initially before acquiring the new knowledge of new mechanisms.

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