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Children’s Core Knowledge about Physics: An Attention-Based Account

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Toddlers’ Core Knowledge about Physics: An Attention-Based Account

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Abstract

A rolling ball cannot pass through a wall, and it will not remain suspended mid-air without support. Studies that investigated children’s knowledge about these principles (also referred to as the solidity and gravity principle, respectively) have yielded inconsistent results. Depending on the details of the task, young children sometimes show a certain degree of sensitivity to the principle, but other times fail to pay attention to it, confounding a core-knowledge account of children’s performance. The current set of experiments was designed to investigate another possible explanation. Namely, that performance depends on the degree to which the immediate task context guides a child’s attention to relevant information. By this attentional account, a moving object might create a temporarily narrowed field of attention along its trajectory. As a result, information outside of that field becomes irrelevant. Experiment 1 focused solely on the principle of solidity and manipulated the degree to which relevant information was within the proposed field of attention. Children between 2 and 3 years old were presented with a movie that depicted a ball that rolled behind a screen containing four doors. Windows in the screen would open and close to allow a portion of a wall (intended to stop the ball) to be visible. The prediction was that when the wall was visible in the child’s proposed field of attention, performance would be successful. Experiment 2 tested the extent to which discrepant performances between violation-of-expectation, search and prediction tasks could be explained under the common framework of attention allocation. Thus, in this experiment all children were asked to perform four tasks (violation-of-expectation, prediction-without-screen, prediction-with-screen and search) in each of two physics domains: Solidity and Gravity. Results from both experiments show a variety of learning effects and idiosyncratic differences in performance among tasks. They further undermine a core-knowledge approach to children’s problem solving and their ability to make sense of the physical world. They point instead to an
approach that takes into account the moment-to-moment allocation of attention as the child navigates through the task.
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CHAPTER 1

Introduction

Over the last two decades, a lot has been said about a young child’s so-called core knowledge of select physical principles. For example, it is argued that even the youngest infants appear to understand that a solid object cannot pass through another solid object (Spelke et al., 1992) – a physical principle known as solidity. Indeed, infants look longer at displays that depict a violation of solidity. Toddlers, too, are sensitive to violations of object solidity. However, this appears to be the case only when assessed with a violation-of-expectation type of looking task (Hood, Cole-Davies & Dias, 2003). When asked to manually search for a hidden object, toddlers do not demonstrate an understanding of object solidity (e.g., Berthier, DuBlois, Poirier, Novak & Clifton, 2000; Hood, Cole-Davies & Dias, 2003; Keen, Berthier, Sylvia, Butler, Prunty, & Baker, 2008; Kloos & Keen, 2005; Mash & Keen, 2003; Mash, Novak, Berthier & Keen, 2006; Perry, Smith, & Hockema, 2008; Perry, Samuelson & Spencer, 2009; Shutts, Keen, & Spelke, 2006). Such conflicting findings about children’s understanding of solidity pose problems for core knowledge theorists. How can infants know something that toddlers fail to draw upon in their problem solving?

Conflicting results about children’s competence are also found in tasks that involve the physical principle of gravity. Core knowledge theory posits that infants show very little understanding of gravity. For example, children seem unsurprised when a falling object appears to stop mid-air (Spelke et al., 1992). On the other hand, toddlers and adults show a strong gravity bias when asked to make predictions about the motion of objects (Hood, 1995; McCloskey, Washburn & Welch, 1993). For example, when children are asked to point to the location where a falling object will stop, they overwhelmingly choose a location directly beneath the starting point—despite visible obstacles that would prevent such motion (Hood, 1995). Similarly, adults
often predict that a ball carried by a person in motion will fall straight down in a linear, vertical trajectory when dropped, ignoring forward momentum of the object (McClosky et al., 1993). How can this discrepancy in findings be explained under a core-knowledge approach to children’s reasoning?

Competing results such as those described above raise the question of whether task performance might be more than merely a reflection of the child’s knowledge. In other words, teasing apart the sources of a child’s performance might be more complicated than a core-knowledge approach implies. The purpose of the following experiments was to explore an alternative explanation for children’s performance during physics-related tasks, namely that children’s performance is driven by the immediate allocation of their attention.

An attention-based approach has been applied successfully to explaining young children’s performance in a variety of tasks, including word-learning tasks (Smith, Jones, Landau, Gershkoff-Stowe & Samuelson, 2002), math-related tasks (Mix, Huttenlocher & Levine, 1996) and categorization tasks (Sloutsky & Fisher, 2008). In each of these cases, drawing attention to relevant information in the immediate context of the task resulted in improved performance. For example, young toddlers were trained to recognize a set of exemplars with novel names, such as “lug” and “zup”, by one characteristic - in this case shape (Smith et al., 2002). After seven weeks of training, children were presented with a set of three testing objects. Each testing object was identical either in color, texture or shape to one of the training exemplars. The task was to identify one of the objects as belonging to a specific category (i.e., children were asked to decide which object was the “lug”). Results showed that children overwhelmingly categorized objects by shape. Surprisingly, children’s object learning success was not confined to the experimental session. Overall, word learning significantly improved
outside of the laboratory. In other words, by directing a child’s attention to object shape as a categorization tool, object word learning was improved in general (Smith et al., 2002).

When attention is focused on relevant information, children show competence; when attention is diverted away from relevant information, children perform poorly. Could the same ideas be applied to better understand children’s performance in physics-related tasks? To explore this question, I will first describe the pertinent physics-related tasks in more detail, and then discuss the degree to which an attentional account could explain the obtained findings.

**Solidity Tasks**

Numerous studies have employed a search task to test toddlers’ knowledge of solidity (e.g., Berthier, Dublois, Poirier, Novak & Clifton, 2000): A ball rolls along a ramp and disappears behind an occluding screen which contains a number of doors arranged along the trajectory of the ball (see Figure 1). A wall is placed on the ramp, adjacent to one of the doors, to interrupt the ball’s trajectory, remaining partially visible above the screen. The ball is then rolled and children watch as it disappears behind the screen. Once the ball has stopped at the wall, children are asked to find the ball. Successful performance requires the child to open the door next to the wall. Across the board, results show that toddlers perform poorly in this task. Even though they are often provided with verbal reminders that the wall stops the ball, performance of 2-year-olds rarely exceeds chance (Gresham & Kloos, 2009; Kloos & Keen, 2005). In fact, either young children guess about the location of the ball, they have a favorite door that they open repeatedly, or they apply another unsuccessful strategy (e.g., Berthier et al., 2000; Perry, Smith & Hockema, 2008). Even 3-year-olds often struggle in this task (e.g., Berthier et al., 2000; Perry, Smith & Hockema, 2008).
While toddlers struggle to find the ball in the search task described above, they perform quite well when no search is required. For example, toddlers look surprised when the experimenter opens the two doors on either side of the wall and the ball appears to have passed through the wall (Hood et al., 2003). Similarly, when the screen is removed (allowing children a full view of the ramp and the wall), they can accurately predict where the ball will stop (Kloos & Keen, 2005). How could an attentional account explain these apparently conflicting findings?

In the case of the search task, children have to integrate the visible portion of the wall with the moving ball, an integration that might be difficult, not only because the two events are spatially separate but also because they differ in salience. The visible portion of the wall – while sufficiently salient on its own – might fade into the background once the much more salient event of a rolling ball takes place. Such effect of changes in salience has been reported before. For example, adults show a tendency to focus their attention to particularly salient cues during visual search tasks, ignoring others (e.g., Eriksen & James, 1986; Posner, Nissen & Ogden, 1978; Treisman & Gelade, 1980). When asked to find a target object amongst a set of distractors, performance is hindered when features of the distractors are more salient than the features of the target (Treisman & Gelade, 1980). This idea is consistent with Piaget’s concept of centration –

*Figure 1. Schematic depiction of a search-task apparatus. A ball rolls behind a screen with four doors and stops at a wall that is seen above the screen.*
the tendency to focus on a particularly salient aspect of an object or display and ignore everything else (Piaget, 1952).

In the case of solidity search tasks, it is possible that the moving object temporarily draws the child’s attention to a narrow field of focus to include only the perceived trajectory of the ball. Task components that lie outside of that field might become irrelevant, at least temporarily, including the visible portion of the wall above the screen. If so, performance should be better if the wall is brought into the child’s field of attention. This was indeed found. In particular, when the wall was modified so that it hung over the screen and was fully visible running alongside the door, performance was improved (Keen et al., 2008). In another example, the wall was extended to be visible both above and below the screen (Gresham & Kloos, 2009). The two visible portions of the wall were moved in tandem between trials – presumably creating a Gestalt that unified the wall, and thus allowing children to ‘see’ the occluded portion of the wall intersecting the ball’s trajectory within their field of attention.

Additional evidence for the importance of children’s allocation of attention in a search task comes from an eye-tracking study with the door apparatus (Kloos, Haddad & Keen, 2006). While the doors were opaque, just like in the original search task, the occluding screen was transparent, allowing intermittent views of the ball rolling behind the screen. Eye-tracking results showed that children who focused on the ball’s trajectory performed very well. After all, the relevant information was visible intermittently in the child’s field of attention (the ball rolling from one door to the next). However, children who momentarily directed their gaze to the wall above the screen, performed near chance. These findings suggest that a child’s allocation of attention is an important factor of their performance in search tasks.

An attentional account could also explain performance in the solidity-related violation-of- expectation tasks. In such tasks, a ball rolls behind a screen and stops at a wall. The screen is
then removed so that children are provided a full view of the ball in its final location. Infants and toddlers look longer at a display in which the ball is shown on the wrong side of the wall, appearing to have passed right through it. The argument is that children look longer at this event because it has violated the laws of physics. However, there is another possibility. Seeing the ball roll along a ramp, disappear, and reappear seconds later might define a narrow field of attention along the length of the ramp; the space between the beginning position of the ball and the final location. Looking time when the ball seems to have passed through the wall might be due to the presence of a wall intersecting the field of attention.

*Gravity Tasks*

Similar to the tasks described above, conflicting results are also found in tasks that involve the principle of gravity. For example, in a violation-of-expectation task, infants watch as a ball drops from above and disappears behind a screen (Spelke et al., 1992). The screen is then lifted to reveal the ball resting on a solid shelf that sits above the surface of a table. After habituation to this event, infants see two test events. In one, the falling ball disappears behind the screen and when the screen is lifted, the shelf has been removed and the ball is shown resting on the table surface. In the other test event, the screen is lifted to reveal a ball that has seemingly stopped mid-air and is suspended above the table. Results show that infants look longer at a ball that is in a superficially novel position (on the table), rather than a ball that has violated the physical principle of gravity (the suspended ball). Such results were interpreted to mean that infants do not have a naïve understanding of gravity and are not sensitive to the physics that guide objects in downward motion (Spelke et al., 1992).

Interestingly, toddlers demonstrate a strong gravity bias, expecting that a dropped object would travel in a downward trajectory despite physical constraints that would make such motion impossible (Hood, 1995). In this task, toddlers watch as a ball is dropped down one of three
openings, each attached to an opaque tube. The three tubes are intertwined so that the ball never travels in a linear trajectory to the bottom of the display. Instead the ball makes a turn to land in a box that is attached to the end of the tube. Children are then asked to find the ball. Successful performance requires the child to reason about the ball’s downward motion within the tube. Results show that instead, toddlers tend to choose the box directly below the opening where the ball was last seen, despite the configuration of the tube (Hood, 1995). This bias complicates a core-knowledge claim that children do not understand the principle of gravity.

Like the solidity findings, gravity findings described above could be explained by an attentional account. For example, infants may seem unsurprised by a ball stopping midair because nothing interferes with the imagined trajectory of the falling object. In other words, unlike the solidity tasks where a wall interrupts the imagined trajectory of the ball, in the gravity task there is nothing new within the narrowed field of attention. Toddlers might make gravity bias errors for a similar reason. The falling ball might draw the child’s attention downward and to a very narrow field that highlights the box directly below the last seen motion. Both of these possibilities lend support to my claim that the moment-to-moment unfolding of events might be as important to task success as the child’s knowledge about the physical principles involved.

Overview of Experiments

The purpose of the following experiments was to investigate the extent to which moment-to-moment attention allocation drives performance in physics-related tasks. The central hypothesis was that successful performance depends on whether the immediate task context guides a child’s attention to relevant information. Thus, I make the following claims: 1) young children’s field of attention is quite narrow and 2) successful performance depends on providing relevant information within the child’s attentional field. Two experiments were conducted to test these claims explicitly.
Experiment 1 focused on solidity and tested the extent to which a toddler’s allocation of attention is defined by a moving object. This was accomplished by modifying the ball-wall display of the search task such that the visibility of the wall could be manipulated (see Figure 2). There were four different levels: The wall was visible (1) in its entire length, well within the trajectory of the ball, (2) immediately below the top of the door, outside the trajectory of a small ball, but within the trajectory of a large ball, (3) half way through the screen, and (4) above the screen. Figure 2c shows the displays for the large-ball condition, and Figure 2d shows the displays for the small-ball condition, each with a specific opening. A dashed line illustrates the presumed attentional field in both conditions. When the opening showed the wall in its entire length, it was predicted that children in both conditions would perform fairly well. However, when the opening showed the wall above the ball’s trajectory, it was predicted that children in both conditions would perform poorly. And when the opening showed the wall below the top of the doors, it was predicted that children in the large-ball condition would out-perform children in the small-ball condition.
Figure 2. Screen shots of the display used in Experiment 1: a) openings at 1 cm. b) openings at 8 cm. c) openings at 14 cm and d) openings at 19 cm. The dotted lines indicate the proposed field of attention for the large-ball (c) and small-ball (d).

Experiment 2 focused on solidity and gravity and pitted different types of tasks against each other: violation-of-expectation, search and prediction tasks. The goal was to test the extent to which performance differences could be explained under the common framework of attention allocation. All children were tested in both the solidity domain and the gravity domain, and their performance was measured in four different kinds of tasks: a type of violation of expectation, two predictions and a search. Figure 3 shows the apparatus that was used. In the violation-of-expectation task, two balls rolled along a ramp and behind a screen. For the solidity domain, one ball had stopped at a wall in its path, and the other had seemingly passed through a wall (see Figure 3a). For the gravity domain, one ball had fallen through the gap in its path, and the other ball had seemingly jumped the gap (see Figure 3b). Children needed to decide which ball had violated the principle of physics (solidity v. gravity). In a prediction-without-screen task, children were asked where a toy dog should stand in order to catch a ball that would roll along the ramp. For the solidity domain, the possible locations were 1) to the left of the wall 2) to the right of the wall or 3) at the end of the base (see Figure 3c). For the gravity domain, the possible locations were 1) to the right of the gap or 2) at the end of the base (see Figure 3d). During a prediction-with-screen task, a screen with three doors occluded a portion of the ramp. During these trials children needed to predict which door the dog must hide behind to catch his ball. Finally, in the search task, children were asked to find a ball that rolled along a ramp and disappeared behind a screen containing the doors. The ball stopped either at a wall that remained only partially visible above the screen (Solidity domain) or at the end of the base of the apparatus (Gravity domain). In each task, attention was manipulated by: making visible the trajectory of
the ball (during the violation-of-expectation and prediction-without-screen tasks), or obscuring it (during the prediction-with-screen and search tasks). Putting all four tasks together in the same display was intended to directly illustrate why violation-of-expectation and un-occluded prediction tasks are traditionally more successful than occluded prediction and search tasks (because relevant information appears in the child’s field of attention only in the former). The expectation was that performance should decline as the relevant information became increasingly occluded, and that in the gravity domain, performance would be less successful, even when the relevant information (the moving ball and the gap) is visible because no cue is available within the proposed field of attention (along the trajectory of the moving ball).
Figure 3. Schematic depiction of the display used in Experiment 2 for the Violation-of-expectation Task and the Prediction-without-screen Task in each domain: Solidity (a and c) and Gravity (b and d).

CHAPTER 2

Experiment 1A

To test whether a moving ball defines the toddler’s allocation of attention, children participated in two conditions that differed in the size of the ball. The task was to point to the door behind which the ball could be found once it rolled behind the screen and stopped at the wall. Within each condition, the wall was visible for its entire length (Fig 2d), partially visible to mid-door (Fig. 2c), partially visible to mid-screen (Fig. 2b), and only above the screen (Fig. 2a). If bringing the visible portion of the wall into the child’s field of attention facilitates the integration of the wall with the motion of the ball, then performance should improve when the windows allow the wall to be seen within the ball’s trajectory. For children in the large-ball condition this would mean performance during trials with openings where the wall was fully visible. When it was visible to the mid-door position, performance should be significantly better than when they were open to mid-screen or closed. Similarly, children in the small-ball condition should show above-chance performance only when the wall was fully visible.

Method

Participants

Children (n = 24) between the ages of 35 months and 47 months were tested in local daycare centers that serve middle class families and a children’s museum. Two children were unwilling to complete the full number of trials and were therefore not included in data analysis. Of the remaining 22 participants (M = 42.15 months, SD = 4.93 months), half (n = 11) were
assigned to the large-ball condition, and the other children \((n = 11)\) were assigned to the small-ball condition.

Materials

A 2D movie presentation was created, using Flash (Adobe, 2000), to mimic the display used by Berthier et al. (2000) and was displayed on a laptop computer with a screen that measured 14 inches in length and 10 inches in height. The computerized display shows a brown “hiding” screen (31 cm long and 21 cm tall) with four red doors measuring 5 cm wide and 5.5 cm tall. The doors were equally spaced 2.5 cm apart. Directly to the right of each door was an opening 2 cm wide, allowing the child to ‘see through’ the screen. A ball was in the leftmost corner of the display.

Each experimental session involved a short familiarization movie that began with the hiding screen. Once the hiding screen was described, it disappeared. Next, the movie depicted a ball rolling along the bottom of a blank display. A wall (21.5 cm tall and 1 cm wide) descended from the top of the display, moving downward and stopped at the bottom of the screen, stopping the ball. The hiding screen then descended from the top of the display and stopped when it was at the bottom of the display (occluding the ball and most of the wall). During the ball-rolling movies, the hiding screen remained in place. On each test trial the wall would descend and come to rest to the right of one of the doors. Depending on condition, the openings in the screen made visible 1 cm, 8 cm, 14 cm or 19 cm of the wall.

Once the wall was in position, the openings closed to mid-screen in order to occlude the ball while it was in motion. Then, a ball (large or small) rolled from left to right and disappeared behind the screen. The large ball measured 5 cm in diameter and was roughly the same height of the doors. The small ball was 2.5 cm in diameter- roughly half the height of the doors. Once the
ball had enough time to travel the length of its trajectory, the openings expanded to their initial size.

There were a total of 32 movies, which differed in the size of the ball (large ball, small ball), the size of the openings (1 cm, 8 cm, 14 cm and 19 cm) and the location of the wall (at Door 1, 2, 3, or 4, with Door 1 referring to the door closest to the starting point of the ball).

Procedure

Children were seated within arm’s reach of a computer screen. An experimenter sat directly to the right of the child and used the computer to display the movies and record the child’s behavior during each trial. The experiment consisted of a short familiarization phase immediately followed by the testing phase.

Familiarization. The experimenter first introduced “Benny the Bird” and then showed the familiarization movie. When the occluding screen appeared, the experimenter said, “This brown thing is the hiding screen and it has four doors. See them? Can you count them with me?” The experimenter then counted the doors along with the child. Then the experimenter said, “Things are going to hide behind the doors and you are going to help Benny find them! Are you ready?” When the ball rolled across the screen, the experimenter noted, “Here comes a ball! It’s rolling!” When the wall descended from the top of the display, the experimenter said “Oh look! A wall is coming down now. It will stop the ball. See? It stopped the ball.” Finally, when the screen descended to hide the ball and wall, the experimenter exclaimed, “Here comes the hiding screen. Remember the hiding screen? It is hiding the ball. We need to find the ball. It is behind one of the doors.” The experimenter then handed the child the feather and said, “Here is a feather from Benny. Can you use your feather to point to the door where the ball is hiding?” After the child pointed to a door, feedback was given (i.e., the doors opened up): The experimenter said, “Look
there is the ball. It stopped at the wall” while pointing to the ball and then running a finger along the length of the wall. The testing trials began immediately.

Testing. Testing trials consisted of showing one of the ball-rolling movies. Within each condition, movies were presented in two quasi-randomized orders. During the first part of a movie, when the screen was visible with its openings, the experimenter said, “There are the windows so you can see right through”. As the wall descended, the experimenter exclaimed, “Now the wall is coming down. It made it all the way to the ground.” Then the experimenter would point to the lower left hand side of the display and say, “Look! Here comes the ball!” After the ball disappeared and the openings expanded, the experimenter then asked, “Where is the ball hiding? Remember, the wall stops the ball.” After four trials a “reward” screen appeared and the child would receive a star sticker. The next set of trials began immediately.

Results

In order to assess performance success, the proportion of correct door selections was calculated for each child. Results of independent-sample t-tests, one for each condition, revealed no effect of order, $ps > .35$. Thus, orders within each condition were collapsed for the remainder of data analysis.

Figure 4 depicts performance separated by ball size and opening. A 2 by 4 mixed-design ANOVA was conducted, with condition (small-ball v. large-ball) as the between-subject factor and opening (1 cm, 8 cm, 14 cm or 19 cm) as the within-subject factor. Results showed no effect of opening, $F(1,20) = .371, p > .75$, no effect of ball size, $F(1,20) = .52, p > .65$, and no interaction, $F(1,20) = .002, p > .90$. Overall, it appears that the openings had little effect on children’s performance: Children performed equally well when the openings were 1 cm as they did when the openings were 19 cm. In fact, overall children performed above chance in all but one case, $ts$
> 2.14, ps < .05. The exception was the performance of children in the large-ball condition during trials when the openings were 14cm, t(10) = 1.5, p > .10. Finally, there was no effect of age, r = .22, p > .35.

![Figure 4](image.png)

**Figure 4.** Proportion correct by opening for children in experiment 1A (the black line signifies chance performance). Error bars represent standard errors.

The next step in data analysis investigated whether or not children showed any signs of learning across trials. Did they get better as they became more familiar with the task? Recall each child received four sets of trials. Children in the small-ball condition did appear to improve across sets (see Figure 5). However, a mixed-design ANOVA with condition (small-ball v. large-ball) as the between-subject factor and set (1, 2, 3 and 4) as the within-subject factor revealed no linear trend, $F(1,20) = 2.16, \ p > .10$. This failure to detect an effect might be due to a marginally significant effect of sphericity, Mauchly’s test $W(5) = .579, \ p < .07$. Inspection of data on the
level of individual children revealed that this effect was most likely driven by three children in the small-ball condition who performed near ceiling in all four sets of trials, whereas all other participants were only successful about half of the time during the first three sets of trials.

Indeed, when the scores from those three children was excluded from analysis, the sphericity test was non-significant ($W(5) = .59, p > .13$) and no linear trend was detected, $F(1,17) = 2.52, p > .13$ confirming that no learning took place across sets.

Figure 5. Proportion correct separated by set for children in Experiment 1A.

Children’s performance appeared not to be affected by how much of the wall they could see during trials, nor did there appear to be any learning across trials. As a final analysis, I compared how children performed based on location of the ball. Did children perform differently when the ball was behind the first or the last door, for example? Or do children have a preferred door? A mixed-design ANOVA with condition (small-ball v. large-ball) as the between-subject factor and Door (1, 2, 3 or 4) as the within-subject factor showed no significant difference in
performance based on ball location, \( F(1,20) = .017, p > .80 \). In other words, children did not seem to show a preference for any particular door (see Figure 6).

![Figure 6. Proportion correct by door for children in Experiment 1A.](image)

Overall results from Experiment 1A showed no effect of the attention-based manipulation. The degree to which the wall was visible did not appear to affect performance in the expected way. In fact, performance was equally successful between trials where the wall was fully visible and those where it was fully occluded. This could have been because the familiarization did not fully explain the openings and their purpose. To explore this possibility Experiment 1B was designed to include a more intensive training session.

**CHAPTER 3**

**Experiment 1B**

Results from Experiment 1A showed no effect of the attention-based manipulation. The degree to which the wall was visible did not appear to effect performance in the expected way.
Children’s above chance performance indicates that they understood something about the task. Surprisingly, however, there was virtually no difference in performance between trials where the wall was completely visible and trials where the wall was almost completely occluded. It seems that if children were performing well when the wall was barely visible, then performance would improve if the wall were fully visible. However, that was not the case. This could have been because the familiarization did not effectively explain the openings and their purpose (to show a portion of the wall behind the screen). As a result the procedure was changed to include more intensive familiarization to the openings and their relationship to the wall.

**Method**

Participants

Children (n = 36) between the ages of 28 months and 45 months (M = 36.2 months, SD = 4.2 months) were tested in local daycare centers that serve middle-class families and a children’s museum. Of those, half (n = 18) were assigned to the *large-ball* condition, and the other children (n = 18) were assigned to the *small-ball* condition. The mean age of children in this experiment was significantly younger than children in Experiment 1A (*t*(56) = 4.74, *p* < .05).

Materials

The computer display and manipulations were identical to those in Experiment 1A (see Figure 2), with the exception of a training movie that was added between the familiarization and ball-rolling movies. The training movie showed the hiding screen, the wall to the right of one of the doors and the openings at 20 cm. The openings were introduced and compared to windows. The openings would then close to 1 cm, 8 cm, 14 cm or 19 cm, changing the degree to which the wall could be seen. Next, the wall appeared next to a different door. The opening was at 20 cm, thus the wall was fully visible. Next the openings would close to 1 cm, 8 cm, 14 cm or 19 cm. For each training movie the wall was shown once with each opening type and once at each door.
Procedure

Familiarization and testing phases were identical to Experiment 1A and are not described here. Different to Experiment 1A was the training, which was administered immediately after the familiarization phase. When the hiding screen and wall appeared the experimenter said, “Here is the hiding screen again, but now it has openings. The openings are a little like windows, because they let us see what’s happening behind the screen. Sometimes the openings let us see the whole wall behind the screen.” The experimenter would then point to the wall saying, “See? The wall goes all the way down to the ground and it always stops the ball.” As the openings closed, the experimenter said, “Now the openings are closing a little, and we can only see this much of the wall.” Pointing to the wall the experimenter said, “but remember, the wall goes all the way to the ground and it always stops the ball.” When the wall appeared next to a different door the experimenter would say, “Now the wall is here. And now the openings are closing and we can only see this much of the wall, but remember, the wall goes all the way to the ground and it always stops the ball.” Testing followed immediately after.

Results

The same scoring was done as in Experiment 1A, and again there was no effect of order for any of the conditions, $ps > .30$). Thus, for the remainder of data analyses, orders were collapsed.

The first analysis was to determine whether performance differed as a function of opening. Figure 7 shows performance for each opening, separated by ball size. A 2 by 4 mixed design ANOVA (with condition as the between-subject factor and opening as the within-subject factor) revealed no effect of opening, $F(3,34) = .73, p > .50$, no effect of condition $F(1,34) = .28, p > .50$ and no significant interaction, $F(3,34) = 1.21, p > .30$. It appears that the size of the opening had little effect on children’s performance. Overall children’s performance was above
chance in all but two instances, $t > 1.96, ps < .05$. The two exceptions were children in the large-ball 1cm condition, $t(17) = 1.06, p > .30$ and children in the small-ball 8cm condition, $t(17) = 1.50, p > .15$. Finally, there was no effect of age, $r = .22, p > .30$.

![Figure 7. Proportion correct by opening for Experiment 1B. Standard errors are reflected in the error bars, and the black horizontal line indicates chance performance.](image)

Figure 7. Proportion correct by opening for Experiment 1B. Standard errors are reflected in the error bars, and the black horizontal line indicates chance performance.

Figure 8 shows performance for children in each condition separated by set, in order to investigate possible learning effects across trials. A mixed design ANOVA with condition (small-ball v. large-ball) as the between subject factor and set (1, 2, 3 and 4) as the within-subject factor revealed a significant linear trend, $F(3,34) = 5.14, p < .04$. Separate repeated-measures ANOVAs, one for each condition, revealed that this effect was likely driven by the performance of children in the small-ball condition where a linear trend was detected $F(3,17) = 2.42, p < .02$. Recall, this same learning trend was suspected for children in Experiment 1A, which was not significant, but worth noting. No linear trend was detected for the large-ball condition, $F(3,17) = .09, p > .76$
Figure 8. Proportion correct separated by set for Experiment 1B. Standard errors are reflected in the error bars.

Figure 9 shows performance as a function of location of the ball. A mixed design ANOVA with condition (small-ball v. large-ball) as the between subject factor and Door (1, 2, 3 and 4) as the within-subject factor revealed a significant effect of door, $F(3,34) = 5.03, p < .01$. Separate repeated measures ANOVAs, one for each condition, revealed that this effect was likely driven by the performance children in the large-ball condition $F(3,17) = 5.06, p < .01$ with children performing significantly better in trials at Door 4 ($M = .56$, $SD = .37$) than at Door 2 ($M = .32$, $SD = .30$) or Door 3 ($M = .26$, $SD = .24$), $ts > 2.05, ps < .05$. What could explain this trend? One possibility is that children expect a large ball to travel further along the display, thus they tend to search further along the ramp. This indeed was found in previous search tasks where toddlers expected faster moving objects to travel further along a ramp (Perry et al., 2008). There was no significant difference between door number in the small-ball condition, $F(3,17) = 1.30, p < .28$. 
CHAPTER 4

Experiment 1 Discussion

The results of Experiment 1A indicate that the main manipulation was ineffective in helping children’s performance by bringing the wall into the proposed field of focus. The results of Experiment 1B further confirmed these findings. Overall, the results of Experiment 1 showed two things: 1) Performance did not differ based on the main manipulation (opening size) and 2) children in both experiments performed better than what was expected by chance. Figure 10 shows performance by opening separated by experiment. A repeated measures ANOVA with Opening (1 cm, 8 cm, 14 cm and 19 cm) as the within-subject factor and Experiment (1A, 1B) as the between-subject factor showed no significant main effect of experiment, $F(3,168) = .45, p > .70$. This indicates that the added training in Experiment 1B had no effect on performance. Across the board, performance was not affected by how much of the wall could be seen within the proposed field of attention. Thus, the hypothesis that performance would differ between

Figure 9. Proportion correct by door in Experiment 1B. Standard errors are reflected in the error bars.
conditions was not supported. Additionally, no age differences were found, with younger children performing as well as older children. While previous studies show that older children are more successful in search tasks (i.e. performance is above chance), the purpose of this study was to detect differences between conditions, not age groups. Thus, older children were tested and a developmental trend was not expected.

Although overall performance in both experiments was better than expected by chance, performance was not as successful as in previous search tasks (e.g. Berthier et al., 2000; Hood et al., 2000). This could be attributed to the task presentation (virtual v. real). It is possible, for example, that the 2D display did not provide sufficient depth cues, thus interfering with the ball-in-motion percept. Indeed, in some object-unity tasks, infants’ performance was affected by depth cues when the display was converted from 3D to a 2D presentation (Johnson & Aslin, 1996).
It is also possible that there were so many motion cues during the ball-rolling movies that it was distracting to the children. After all, the openings not only needed to expand and close between trials, they needed to close temporarily within a trial to occlude the motion of the ball. The added movement on the screen could have been so distracting that children needed to ignore the main manipulation in order to focus on the real task – finding the ball. In this scenario, children would focus on the motion of the ball and only after being asked to point to the ball’s final location did they take notice of the wall. This could explain why there was no effect of the size of opening. Another explanation could involve working memory and cue integration. In order to perform successfully, children needed to remember where the wall ‘landed’ as it descended from the top of the screen. If children could make a connection between the wall and the door before the ball began rolling, then they simply needed to integrate the remembered location with the path of the occluded ball. Previous studies have shown that children older than 2.5 years old are quite good at doing just that (e.g. Butler et al., 2002).

However, there is one other possibility. Specifically that motion did create a field of attention, but not along the path of the ball. Recall, the openings allowed children to see varying views of the wall. The prediction was that when the wall was visible along the field of attention children would take notice. However, the size of the opening only matters if the field of attention is along the path of the moving ball. It is possible that the wall descending from the top of the screen was so attention grabbing that the field of attention was along the vertical path of the wall, and not the horizontal path of the moving ball. In other words, if a child’s attention is focused...
along the trajectory of the wall, the motion of the ball becomes irrelevant and successful performance involves searching behind the door closest to the field of attention.

The results of Experiment 1 highlight the complexity of attention allocation during tasks that require children to integrate many pieces of information. This is especially true when some of the vital information is occluded. Successful performance in search tasks usually requires a child to reason about hidden motion – something that children seem to be quite good at (e.g., Johnson & Aslin, 1995; Perry et al., 2008). However, in manual search tasks, the motion of the ball is so attention grabbing that often other pieces of information (such as the wall that will stop the ball) are ignored. Indeed, when relevant information is visible and children need not ‘imagine’ where a ball or wall might be performance is quite good (Hood et al., 2003; Kloos & Keen, 2005; Mash et al., 2006). To this end, another experiment was designed to explicitly test the possibility that when information relevant to task success is fully visible, performance is significantly better than when important information is occluded.

CHAPTER 5

Experiment 2A

The purpose of Experiment 2A was to investigate children’s understanding in two different knowledge domains: Solidity and Gravity. Within these domains, performance differences are consistently found between violation-of-expectation tasks, manual search tasks and prediction tasks, as described earlier. These discrepancies could be explained under the common framework of attention allocation. The specific hypothesis was that children are able to reason about solidity, but only when the relevant information (in this case a wall that intersects the path of the ball) is fully visible. Otherwise, the attention grabbing motion of the ball might draw a child’s attention to a narrow field of focus and relevant cues outside of the attentional field might become peripheral in solving the task. In a task that requires children to reason about
gravity, however, performance might not be as successful, even when all of the relevant information is visible. This is because a gap below the field of attention is much less salient than a wall intersecting a narrowed field of focus. An apparatus similar to the one used by Spelke et al., (1992) was used. Children were asked to identify a moving object that had violated the principle of object solidity (or gravity), to predict where a moving ball would stop, and to search for a ball that rolled behind a screen and stopped behind one of three doors.

Method

Participants

Toddlers \((n = 22)\) between 29 and 47 months of age \((M = 36.6 \text{ mo}, SD = 5.5 \text{ mo})\) were tested in local daycare centers serving primarily middle class families and a children’s museum. Half of the children \((n = 11)\) were tested in the Solidity domain first and half of the children \((n = 11)\) were tested in the Gravity domain first.

Apparatus and materials

The ramp apparatus used for this experiment is shown in Figure 3. The base of the apparatus was 82 cm long and 20 cm deep. A ramp of same dimensions was attached 18 cm above the base. It had a gap 31.5 cm wide separating the beginning of the ramp and the end of the ramp. A second ramp could be placed on top of the gap-ramp to cover the gap. A piece of wood, 36 cm tall and 20 cm deep, was attached to the end of the apparatus to prevent the ball from rolling off the edge. Two dowel rods (5 mm in diameter) ran horizontally along the length of both ramps, placed 6 cm apart, to constrain the motion of a ball that was used during trials. A white piece of foam (18 cm tall and 82 cm long) could be placed behind the base to occlude any movement or distractions behind the apparatus. Two small pieces of wood (15 cm long and 2 cm tall) constrained the motion of the ball on base. The entire apparatus was painted white.
A series of four foam balls was used, each 6 cm in diameter and painted green, yellow, orange or purple. A wall measuring 2 cm wide, 45 cm tall and 20 cm deep was used during trials in the solidity domain. It had two small blocks (1 cm square) attached to either side to stabilize it when placed on the ramp. Two screens were used to occlude a portion of the ramp during some trials. They were both 40 cm high and 33 cm wide, and they were constructed of solid white foam. The plain screen had no openings, while the door screen contained three doors (14 cm wide x 18 cm high). Two of the doors were centered at the top of the screen and were spaced 6 cm apart. The third door was located 1 cm directly below the right-most door (see Figure 3c).

Other materials included a small toy dog named “Farley”, a small laminated picture of Farley and place markers 3.5 cm square and ‘tented’ so they would stand independently. Additional materials were used during the familiarization trials. These included a small plastic duck, paper cutouts (one of a pond and the other of a tree) and two yellow balls that were 8 cm in diameter: 1) a plain ball and 2) a cowgirl ball (a yellow ball wearing a pink hat and boots). Other testing materials included a plain red bookmark and stickers that were used as a means of encouragement.

Procedure

Children sat within reaching distance of the apparatus. One experimenter (E1) sat behind the apparatus and conducted the experiment. Another experimenter (E2) sat directly to the right of the child and provided assistance to E1 in placing the screens in front of the apparatus when needed. E2 also helped to keep the child seated and engaged.

Familiarization. E1 placed Farley and a yellow ball on the ramp and said, “This game is called Hide and Seek with Farley. Farley likes to play hide and seek with his ball.” Next, the door screen was placed in front of the ramp. E1 said "We are going to use these doors in our hide and seek game. Can you point to each door and count with me?" E2 pointed to each door,
encouraging the child to do the same as they counted. E1 then placed the toy duck, pond, and tree on the table and said, “This is my duck, where should he go swim?” Pointing to the tree and then to the pond the experimenter asked, “Should he swim here or here?” Once the child pointed to the pond, the next phase of familiarization began. The purpose of this task was to get the child to point, so correct vs. incorrect choices were not recorded. If the child pointed to the tree E1 simply said, “No, the duck swims in the pond, not on the tree. Can you point to the pond?”

Finally, E2 placed the plain ball and the cowgirl ball on the table and said, “Look, at these two balls. One of the balls is playing a trick. Do you know what a trick is? It is when something is doing what it is not supposed to do.” E1 then asked, “Which ball is playing a trick?” Once the child responded, E1 picked up the cowgirl ball and said, “Yes (or “no” if the child chose the plain ball), this is the tricky ball because balls don’t wear hats or shoes”. The balls were put away and E2 said, “Farley is so happy that you are playing today, and he wants to give you stickers as we play the game.” E1 then handed the child the bookmark and asked, “Are you ready to play?”

*Test Trials.* All children were tested in two domains: *Solidity* and *Gravity*, and there were four tasks for each domain: *Violation-of expectation, Prediction-without-screen, Prediction-with-screen* and *Search*. Each task was presented in order two times, for a total of 16 trials. Below is the procedure for each of the tasks, separated by domain:

*Solidity*

First was the violation-of-expectation task. E2 placed the plain screen front of the ramp and E1 said, “Let’s watch Farley’s balls roll on the ramp”. E1 would then roll the yellow ball followed by the green ball. Once the balls stopped at the end of the ramp, the screen was lifted to reveal the balls in their final location. No feedback was provided. E1 then removed the balls and placed the wall approximately ¾ of the way down the ramp. The plain screen was placed in front
of the apparatus and the E1 said, “Let’s watch Farley’s balls roll on the ramp”. E1 held up the yellow and green balls. The balls were rolled one at a time and disappeared behind the screen. While the second ball was rolling, the experimenter secretly caught first ball and placed it on the other side of the wall (from the child’s perspective it was to the right of the wall). Once the balls were in place, the screen was removed and E1 said, “Which ball played a trick on Farley?” Once the child pointed to one of the balls, they were removed from the ramp and the prediction-without-screen task began.

During the prediction-without-screen task, Farley was placed on the leftmost side of the ramp. E1 put the place markers in three positions. From the child’s perspective they were: 1) to the left of the wall 2) to the right of the wall and 3) at the end of the base. E2 would point to all three of the markers while E1 asked, “Should Farley stand here, here or here?” After the child pointed to one of the place markers, E2 moved Farley to that location and E1 said, “Let’s watch Farley’s ball roll on the ramp”. E1 then rolled the yellow ball. When the ball stopped, E1 said either “Farley caught his ball” or “Farley didn’t catch his ball”.

Next, the door screen was placed in front of the ramp and the prediction-with-screen task began. E1 said, “Here are my doors. Which door should Farley stand behind in order to catch his ball? Should Farley stand here, here or here?” E2 would point to each of the three doors. Once the child made a choice, E2 would place the laminated picture of Farley on the chosen door and immediately remove the screen from the ramp. Once the screen was removed, the child was given a sticker (as a means of encouragement). No feedback was given after prediction-with-screen trials. Next was the search task and E1 would say, “Look, here come the doors again” as E2 placed the door screen in front of the ramp. E1 then said, “Let’s watch Farley’s ball roll on the ramp.” Once the yellow ball rolled behind the screen and stopped at the wall E1 asked,

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1 Each ball was rolled first once to avoid any association between ball color and the violation of physics.
2 Each ball was rolled first only once to avoid any association between ball color and violation of physics.
“Which door should Farley look behind to find his ball?” Once the child pointed to a door, E2 open it to allow the child to see if the ball was there. E1 then said, “Farley found his ball.” If the wrong door was chosen, E1 said, “Farley didn’t find his ball”.

*Gravity*

During the two violation-of-expectation trials, E2 placed the plain white screen in front of the ramp and E1 said, “Let’s watch Farley’s ball roll on the ramp.” E1 then rolled the orange ball and the purple ball along the ramp, one after the other. After both balls disappeared behind the screen and stopped at the end of the ramp, the screen was lifted to reveal the balls in their final location. No verbal feedback was provided. E1 then removed a portion of the solid ramp (along with the white board attached to the back of the lower ramp) to reveal the gap ramp. The plain screen was placed in front of the apparatus and the experimenter said, “Let’s watch Farley’s balls roll on the ramp.” The orange ball and the purple ball were rolled one after the other and disappeared behind the screen. E1 surreptitiously caught the balls as they went behind the screen and placed one ball on the opposite side of the gap, and the other directly below, at the end of the base. Once the balls were in place, the screen was removed E1 said, “Which ball played a trick on Farley?” Once the child made a choice, the balls were removed from the ramp and the prediction-without-screen task began.

Farley was placed on the leftmost side of the ramp. The child was asked where Farley should stand to catch his ball. E1 put the place markers in two positions: 1) at the end of the upper ramp (from the child’s perspective this was to the right of the gap) and 2) at the end of the base. E1 would ask, “Should Farley stand here, or here?” and E2 pointed to each of the possible locations. After the child pointed to one of the place markers, E1 moved Farley to that location and said, “Let’s watch Farley’s ball roll on the ramp”. E1 then rolled the orange ball and said,

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2 Each ball was rolled first only once to avoid any association between ball color and violation of physics.
“Farley caught his ball” or “Farley didn’t catch his ball”. Next, the door screen was placed in front of the ramp and the prediction-with-screen task began. The procedure for the prediction-with-screen and the search tasks were identical to the procedure used in the solidity domain and involved the orange ball. The door screen was used, so the gap was fully occluded.

**Results**

Children participated in two trials per task within each of the two domains. For each trial, performance was coded in terms of whether the child’s choice (i.e., choice of ball in the violation-of-expectation tasks, or choice of location in the other tasks) was correct or incorrect. The probability of performing correctly by chance alone was .50 in the gravity prediction-without-screen and all violation-of-expectation tasks (because there were two answer options, only one of which was correct), and .33 in the remaining tasks (because there were three answer options, only one of which was correct). Given these differences in chance probability, performance cannot be compared across tasks. Figure 11 compares children’s performance in relation to chance in each domain. For data analysis a series of 2 by 2 ANOVAs were run (one for each task)\(^3\). Results are reported below for each domain and separated by task.

**Violation-of-Expectation Task in the Solidity Domain**

For this and all subsequent tasks, a 2 by 2 mixed-design ANOVA was conducted, with trial (Trial 1 v. Trial 2) as the within-group factor and order (Solidity-first v. Solidity-second as the between-group factor. The analysis revealed no significant effect of trial, \(F(1,20) = .18, p > .60\), nor a significant interaction, \(F(1,20) = .18, p > .60\). However, there was a significant effect of order, \(F(1,20) = 9.60, p < .01\); \(\chi^2(1) = 3.06, p < .09\). Children who received the solidity task second performed better (\(M = .77, SD = .34\)) than children who received the solidity task first (\(M = \ldots\))

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\(^3\) Each child produced only one score for each condition, limiting the power of the test by means of increased error variance. Therefore I report marginal effects as well. Each significant main effect is followed up with a chi-squared test. For the chi-square tests, children are categorized as either successful or unsuccessful.
Single-sample t-tests revealed above-chance performance for children in the former case, \( t(10) = 2.63, p < .03 \), but not in the latter, assuming a chance probability of .50\(^4\). In fact, performance for children who received the solidity task first was marginally below chance, \( t(10) = 1.83, p > .08 \), suggesting that children might have had a preference for the last seen ball. After all, children in the solidity-first order had limited exposure to the task at the time performance was measured. Finally, there was no effect of age (\( r = .16, p > .40 \)).

Overall results were in the direction of the prediction. When relevant information (the balls and the wall) was in full view, children could recognize that one ball had seemingly passed through the wall. However, this was only the case when children had previous experience with violation-of-expectation tasks (from the task in the gravity domain), during which they could get acclimated to the task.

**Prediction-without-screen Task in the Solidity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effects or interactions, \( F_s < 1.5, ps > .25 \). Across trial and order, performance was not significantly above chance, \( t(21) = 1.07, p > .25 \), assuming a chance probability of .33 (\( M = .43, SD = .44 \)). In other words, children struggled to predict where the ball would stop even though the wall was in full view. Finally, there was no effect of age (\( r = .17, p > .20 \)). This finding was surprising, because previous research has shown that children are quite good at predicting where a moving object will stop (Kloos & Keen, 2005).

**Prediction-with-screen Task in the Solidity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant interaction, \( F(1,20) < 1, p > .90 \). However, both main effects were significant (effect of trial: \( F(1,20) = 6.42, p < .02; \chi^2(1) = 4.70, p < .04 \); effect of order: \( F(1,20) = 8.43, p < .01; \chi^2(1) = 4.21, p < .05 \). In terms of trial

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\(^4\) Given that there was no effect of trial, children’s performance across the two trials was collapsed into an average.
effect, performance on the first trial was lower ($M = .27, sd = .32$) than performance on the second trial ($M = .64, SD = .33$). When compared to chance (.33), performance during the second trial was significantly above chance ($t(21) = 2.91, p < .01$), but not performance in the first trial, $t(21) = .58, p > .50$. While these results were not predicted, they indicate that the feedback after the first trial might have helped to improve performance.

In terms of the order effect, children who received the solidity task first performed better ($M = .64, SD = .32$) than children who received the solidity task second ($M = .27, SD = .27$). It appears as though the participation in the gravity task, prior to the solidity task, biased children to perform consistently incorrectly (rather than perform at chance). Indeed, upon inspecting the data more carefully, it turns out that 8 out of 11 children from the solidity-second order chose Door 3 behind which to place Farley on the first trial. This proportion is greater than what would be predicted by chance alone (assuming a chance probability of .33; binomial $p < .05$). The proportion of correct performance on this first trial was indeed significantly below chance, $t(10) = 2.6, p = < .03$). Children having seen the ball repeatedly behind Door 3 in the gravity task might have biased them to place Farley in that same location in the subsequent solidity task. Feedback on one prediction trial was sufficient to remove that bias, yielding better performance on the second trial. There was no significant effect of age ($r = .07, p > .40$).

**Search Task in the Solidity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effect of trial and no interaction, $Fs < 1.0, ps > .30$. However, a marginally significant effect of order was found, $F(1,20) = 3.85, p < .07$; $\chi^2(1) = 2.29, p > .10$; with children in the Solidity-first order ($M = .68, SD = .46$) performing better than children in the Solidity-second order ($M = .32, SD = .40$). Indeed, single-sample t-tests, on data combined across trials, revealed that performance was significantly above chance in the Solidity-first order, $t(10) = 2.5, p < .04$, but not in the Solidity-
second order, \( t(10) = .09, p > .90 \), assuming a chance probability of .33. It is possible that children benefitted from the feedback provided during the prediction tasks, performing better than what would be predicted on the basis of previous task. This benefit might have been lost for children who were presented with the solidity task second, because they were biased to search at a location that was correct on a previous trial. There was no effect of age (\( r = .09, p > .50 \)).

**Figure 11.** Performance relative to chance for each domain in Experiment 2A, separated by order and number of trial. The dotted line represents chance performance.

**Violation-of-Expectation Task in the Gravity Domain**

For this and all subsequent tasks, the same 2 by 2 mixed-design ANOVA was conducted that was used for the solidity task, with trial (Trial 1 v. Trial 2) as the within-group factor and order (Gravity-first v. Gravity-second) as the between-group factor. Here, the analysis revealed no significant main effects or interactions, \( Fs < .20, ps > .90 \), and performance (\( M = .54, sd = .40 \)), collapsed across trials, was not significantly above chance, single-sample \( t(22) = .52, p > .50 \), assuming a chance probability of .50. In other words, children had difficulty deciding which ball defied the principle of gravity, even when the gravity task came second, after the solidity task. This result is starkly different from the performance in the corresponding solidity task,
where children performed well, after some exposure to the task. The result is consistent with Spelke et al. (1992), who reported successful performance in the solidity task (Exp. 3), but not in their gravity task (Exp. 4). No effect of age was found ($r = .15, p > .50$).

**Prediction-without-screen Task in the Gravity Domain**

The 2 by 2 mixed-design ANOVA revealed a marginally significant effect of trial, $F(1,20) = 4.0, p < .06; \chi^2(1) = 2.41, p > 10$; with children performing better on the first trial ($M = .73, SD = .47$) than on the second trial ($M = .54, SD = .50$). When compared to chance (.50 in this case), performance was significantly above chance during the first trial, $t(21) = 2.53, p < .03$.

But not the second, $t(21) = .41, p > .60$. Recall that there was no trial effect in the prediction-without-screen task of the solidity domain. Why would children’s performance drop when the task is repeated? Upon further inspection of the data, no specific patterns emerge. This is difficult to explain, and requires further investigation. No other significant effects were found, whether main effect or interaction, $Fs < 1.0, ps > .50$. Finally, there was no effect of age ($r = .09, p > .45$).

**Prediction-with-screen Task in the Gravity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effects or interaction, $Fs < 1.3, ps > .25$. A single sample t-test (with values collapsed across trials) revealed no significant difference from chance, assuming a chance probability of .33, $t(21) = 1.14, p > .25$ ($M = .43, SD = .41$). As expected, children struggled to find the ball, especially now when relevant information was fully occluded. Again, there was no effect of age ($r = .24, p > .25$).

**Search Task in the Gravity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effect of trial nor a significant interaction, $Fs < .75, ps > .40$. However, a significant effect of order was found, $F(1,20) = 5.07, p < .04; \chi^2(1) = .91, p > .30$; with children in the Gravity-first order performing
significantly better ($M = .55, SD = .41$) than children in the Gravity-second order ($M = .18, SD = .33$), $t(20) = 1.71, p < .04$. When compared to chance, neither group of children performed significantly better than chance, $t < 1.75, ps > .10$. Children in the gravity-second order were biased toward choosing Door 1, the location that was correct on the solidity search task, presented prior to the gravity task. Indeed 8 of 11 children in the gravity-second order chose Door 1 in the first trial, a proportion that is higher than what would be predicted by chance alone (assuming a chance probability of .33; binomial $p < .05$). Like performance in the prediction-with-screen in the solidity domain, this finding highlights the relevance of the child’s immediate history in biasing them to perform in a certain way. Finding that children perform at chance, even when they did not participate in a prior task that biased them to the incorrect choice, implies – as predicted – that a physics task that occludes relevant information in the immediate field of attention handicaps children’s reasoning. Finally, there was no effect of age ($r = .21, p > .40$).
**Figure 12.** Proportion correct for each child ($N = 22$) in the Gravity Domain in Experiment 2A separated by task. The solid lines are for children $> 36$ months, and the dotted lines represent children $< 36$ months old. Scores were collapsed across trial number and order, yielding possible outcomes of 0, .5 and 1. For increased visibility, overlapping scores were given scores slightly above or below the possible scores.

**Figure 13.** Proportion correct for each child ($N = 22$) in the Solidity Domain in Experiment 2A separated by task. The solid lines are for children $> 36$ months, and the dotted lines represent children $< 36$ months old. Scores were collapsed across trial number and order, yielding possible outcomes of 0, .5 and 1. For increased visibility, overlapping scores were given scores slightly above or below the possible scores.
The overall results of Experiment 2A highlight how small changes in the immediate context can change performance. Children’s overall performance was no better than expected by chance during most of the tasks, regardless of whether or not the relevant information was in full view or occluded. There were a few exceptions, of course. During the violation-of-expectation task in the Solidity domain, children who had previous experience with a violation-of-expectation task (Gravity-first order) excelled at determining which ball had ‘tricked’ Farley. Perhaps after multiple trials they learned what ‘tricky’ meant. However, children in the Gravity-second order did not enjoy the same effect; their performance did not reach above chance levels, even after several violation-of-expectation trials. In essence, children’s performance was appeared random and no specific patterns were detected in either domain. Figures 12 and 13 depict children’s individual performance in each task within a domain. There is no clear explanation for the disordered outcomes found in this experiment. However, the significant order effects found in several tasks, paired with the potential learning effects could be the result of experience with the apparatus and the feedback that was provided. In order to explore this possibility, the experimental design was adjusted and Experiment 2B was conducted.

CHAPTER 6

Experiment 2B

The purpose of Experiment 2B was to address the issue of order effects found in Experiment 2A. It is possible that the feedback provided to the children had an effect on their performance. As a result, the procedure was changed in three ways: First, no feedback was given to the children. Second, a separate ball was used on all trials that were not ‘tricky’. This was an additional measure added to prevent any association of color with the concept of ‘tricky’ (the term used during the violation-of-expectation trials). Third, an additional marker was added
to the prediction-without-screen trials in the Gravity domain. This was done in order to maintain consistency between domains.

Method

Participants

Toddlers \((n = 35)\) between 29 and 47 months of age \((M = 37.5 \text{ mo}, SD = 4.7 \text{ mo})\) were tested in local daycare centers serving primarily middle class families and a local children’s museum. All children were tested in two domains: Solidity and Gravity. Nineteen of the children were tested in the Solidity domain first. Sixteen children were tested in the Gravity domain first.

Apparatus and materials

The Apparatus and materials were identical to Experiment 2A with one exception: For all non-‘tricky’ tasks (prediction-without-screen, prediction-with-screen and search) a black ball was used. The purpose of this change was to avoid any association of color with the meaning of tricky.

Procedure

Familiarization. Familiarization trials were identical to Experiment 2A and are not explained here. Test trials began immediately.

Test Trials. The procedure for test trials was identical to Experiment 2A, with a few exceptions: In the tasks that only required one ball (Prediction-without-screen, prediction-with-screen and search) a new black ball was used during the trials. When using the black ball E1 would always say, “This ball NEVER plays a trick on Farley” before rolling the ball. Another change in procedure related to the prediction-without-screen tasks in the Gravity domain. Different from Experiment 2A, E1 placed three markers (rather than two) on the apparatus: 1) to the left of the gap 2) to the right of the gap and 3) at the end of the base. The final change in procedure involved verbal feedback. This effected the procedure in two of the tasks: prediction-
without-screen and search. In each of the tasks the child was asked to make a choice (where Farley should stand to catch his ball or which door he should look behind to find his ball). Recall in the prediction-without-screen once the child made a choice, E1 would roll the ball and provide verbal feedback (i.e. “Farley found his ball” or “Farley didn’t find his ball”). However, in the new procedure E1 would place Farley in the chosen location and roll the ball. Once the ball stopped E1 said nothing and the ramp was prepared for the next task. Similarly, in the search task E1 would roll the ball behind the door screen. Once the ball stopped behind the screen E1 asked the child “Which door should Farley look behind to find his ball?” The child was allowed to make a choice, but the door was not opened and no verbal feedback was provided. Instead, the ball and screen were removed and the next trial began immediately.

Results

Figure 14 shows the performance in Experiment 2B compared to chance in each domain. As was done before, a series of 2 by 2 mixed-design ANOVAs were conducted, with trial (Trial 1 v. Trial 2) as the within-group factor and order (Solidity-first v. Solidity-second) as the between-group factor. Significant main effects ($p < .05$) and marginally significant effects ($p < 0.1$) were followed up by a chi-squared test.

Violation-of-Expectation Task in the Solidity Domain

The ANOVA revealed no significant effects of trial, $F(1,33) = .02, p > .90$, or order $F(1,33) = .05, p > .60$, and no significant interaction, $F(1,33) = .27, p > .60$. Once scores were collapsed across order and trial number, a single-sample t-test revealed that performance ($M = .48, SD = .39$) was not significantly above chance, $t(34) = .21, p > .80$, assuming a chance probability of .50. Overall, children did not successfully choose the ball that had violated the principle of solidity. This could be attributed to a lack of understanding. Maybe children were
unclear as to what the word ‘tricky’ meant in a task that did not involve a ball with a hat and boots.

Prediction-without-screen Task in the Solidity Domain

The 2 by 2 mixed-design ANOVA revealed a marginally significant main effect of trial, $F(1,33) = 3.53, p > .06; \chi^2(1) = 3.28, p < .08$; and a significant effect of order, $F(1,33) = 11.74, p < .01; \chi^2(1) = .00, p > .90$. Because the effect of trial was only marginally significant, scores were collapsed across trials. Results of two single-sample t-tests revealed performance was significantly above chance for children in the Solidity-first order ($M = .59, SD = .49), t(31) = 2.99, p < .01$ but significantly below chance for children in the Solidity-second order ($M = .18, SD = .39), t(36) = 2.15, p < .04$, assuming a chance probability of .33. A closer look at the data did not reveal any obvious pattern that could explain the below chance performance. No significant interaction was found, $F(1,33) = 1.72, p > .19$, and there was no effect of age ($r = .08, p > .50$). Overall results were in the predicted direction. When relevant information (the balls and wall) was in full view, children could recognize that a ball would not pass through a wall. However this was only the case when children had little previous experience. How can the poor performance of children in the Solidity-second order be explained? All children saw the same display, and the wall was fully visible while the child predicted where Farley should stand. Perhaps previous experience with prediction-without-screen trials had an effect on performance. For example, it is possible that completing the task in previous trials, with no feedback, confused the children and thus, they resorted to guessing on subsequent prediction-without-screen tasks.

Prediction-with-screen Task in the Solidity Domain

The 2 by 2 mixed-design ANOVA revealed a no significant main effects or interactions, $Fs < .40, ps > .50$. Scores collapsed across trial and order ($M = .45, SD = .40$) was found to be marginally above chance, $t(34) = 1.83, p < .07$. Overall, children struggled to find the ball when
the relevant information was occluded. Such findings support my claim that performance is less successful when important information is occluded. No effect of age was detected ($r = .31, p > .09$).

**Search Task in the Solidity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effects or interaction, $Fs < 1.3, ps > .57$. Scores were then combined across trial and order and compared to chance. A single-sample t-test showed that performance ($M = .44, SD = .41$) was not significantly above chance $t(34) = 1.60, p > .10$, assuming a chance probability of .33. The prediction that children would not perform well during trials where most of the relevant information was occluded was supported. Finally, there was no effect of age ($r = .10, p > .50$).

![Graph showing performance for each domain in Experiment 2B separated by order and compared to chance. The dotted line represents chance performance.](image)

**Violation-of-Expectation task in the Gravity Domain**

The ANOVA revealed no significant main effects or interactions, $Fs < .29, ps > .55$. Given no significant effect of trial or order, scores were combined into one proportion and compared to chance. A single-sample t-test revealed that performance ($M = .48, SD = .47$) was
not significantly above chance, $t(34) = .17, p > .50$, assuming a chance probability of .50. Overall children did not appear to be able to decide which ball defied the principle of gravity, even when the gap was in full view. No effect of age was found ($r = .23, p > .40$).

**Prediction-without-screen Task in the Gravity Domain**

Two children would not make a prediction in this task. Therefore, no score was recorded for these participants and those trials were not included in the analysis. Additionally, coding was slightly different in this task. Recall, after changes in procedure the children were given three choices as to where Farley could stand to catch the ball (to the left of the gap, to the right of the gap and at the end of the lower ramp). Technically, two of these choices could have been correct: If Farley was to the left of the gap, he would have caught the ball before it fell into the gap. If he stood at the end of the base, the ball would have dropped through the gap and continued along until it reached him. Thus, chance probability changes to .66 for this task.

The ANOVA revealed a significant main effect of trial, $F(1,32) = 4.95, p < .04; \chi^2(1) = 2.87, p > .09$; with performance for children in both orders getting worse during the second trial. This same trend was seen in Experiment 2A as well, indicating that this effect is robust, but difficult to explain. Two single-sample t-tests revealed that performance was not significantly above chance for Trial 1 ($M = .72, SD = .42$) or for Trial 2 ($M = .51, SD = .50$), $t_s < 1.51, ps > .14$, assuming a chance probability of .66. No significant interaction was found, $F(1,32) < 1.0, p > .60$.

For comparison, data was re-coded to reflect how many children chose the location on the base only. In other words, when the locations on the upper ramp (to the left of the gap and to the right of the gap) were both coded as incorrect, was there still an effect of trial? The ANOVA revealed no significant main effects or interaction, $F_s < 1.0, ps > .50$, with Gravity-first children performance ($M = .35, SD = .50$) and Gravity-second performance ($M = .44, SD = .50$) no
different than chance, \( t(32) = .99, p > .30 \), assuming a chance probability of .33. This finding further indicates that children have difficulty predicting where a ball will stop, even when relevant information is in full view. No effect of age was detected \((r = -.08, p > .60)\).

**Prediction-with-screen Task in the Gravity Domain**

The 2 by 2 mixed-design ANOVA revealed no significant main effects or interactions, \( Fs < 1.1, ps > .30 \). Thus, scores were collapsed across trial and order. A single sample t-test showed that overall performance \((M = .32, SD = .40)\) was not significantly above chance, \( t(34) = .02, p > .90 \), and no effect of age was detected \((r = .34, p > .10)\). Overall, the results were in accord with the prediction that performance would not be successful during trials where relevant cues are occluded. After all, the gap could not be seen once the door-screen was in place. Thus, no relevant information as to the location of the ball was available to children.

**Search Task in the Gravity Domain**

The 2 by 2 mixed-design ANOVA showed no significant main effects or interaction, \( Fs < 1.50, ps > .24 \). Again, scores were collapsed across trial and order. A single sample t-test showed that overall performance \((M = .41, SD = .39)\) was not significantly above chance, \( t(34) = 1.27, p > .20 \), assuming chance probability of .33, and no effect of age was detected \((r = .28, p > .09)\). These results show that children could not successfully choose the door where the ball would stop once it rolled behind the screen, again supporting the claim that when attention is allocated to an area where no vital information is seen, performance suffers.

The overall results from Experiment 2B show that children were not sensitive to violations of physical laws (or they did not understand what was meant by the word “tricky”) and that once the ramp was occluded, performance was not better than expected by chance even when slight cues were provided (the visible portion of the wall during testing in the Solidity domain). Interestingly, in prediction tasks where the gap and wall were in full view (prediction-
without-screen), conflicting results showed that the performance of children who were tested in the Gravity domain first gradually got worse with each prediction-without-screen trial.

CHAPTER 7

Experiment 2 Discussion

The overall prediction for Experiment 2 was that when information important to task success is in full view, children should have little difficulty reasoning about the physics that guide moving objects. Thus, the expectation was that during the violation-of-expectation and prediction-without-screen tasks performance would be quite good and then decline once task events were occluded (during prediction-with-screen and search tasks). Overall, children did perform poorly in tasks where relevant information was occluded. Surprisingly, however, we found that they perform just as poorly when task events were in full view, with two exceptions: In Experiment 2A, children in the gravity-first order were very successful in determining which ball had violated the physical principle of solidity, and in Experiment 2B, children performed better when initially asked to predict where the ball would stop on an un-occluded ramp.

CHAPTER 8

General Discussion

The purpose this set of experiments was to investigate the extent to which moment-to-moment attention allocation drives performance in physics-related tasks. The central hypothesis was that successful performance depends on whether the immediate task context guides a child’s attention to relevant information. In Experiment 1 this was investigated by manipulating two factors: the size of the attentional field and the amount of relevant information in that field. In Experiment 2 this was investigated by combining violation-of-expectation, search and prediction tasks into a single experimental session. The findings from both experiments illustrate the complicated nature of attention and how sensitive children can be to changes in the immediate
Experiment 1 tested the extent to which a toddler’s allocation of attention is defined by a moving object. This was accomplished by creating a series of movies that depict events often found in search tasks that require children to reason about object solidity (e.g., Berthier et al., 2000; Hood et al., 2003; Keen et al., 2008; Kloos & Keen, 2005; Mash & Keen, 2003; Mash et al., 2006; Perry et al., 2009; Perry et al., 2008; Shutts et al., 2006). In review: Solidity search tasks involve a ball that rolls behind a screen containing a set of doors. A wall is placed in the path of the ball and remains partially visible above the screen and adjacent to one of the doors. Successful performance requires a child to keep in mind the hidden information—the mostly occluded wall and the moving ball. Overall, children struggle to successfully find the ball, even though there is some information in the task display that provides a cue as to the location of the ball (the visible portion of the wall).

My claim was that a moving ball is so attention grabbing that it temporarily narrows a child’s field of attention to a very small portion of the screen, well below the relevant information (the visible portion of the wall). Thus, the assumption was that bringing the visible portion of the wall into the temporarily narrowed field of attention would facilitate successful performance. Overall results did not support this prediction. In fact, children performed quite well, regardless of how much of the wall was visible: Children performed above chance when the wall was in full view and when it was almost completely occluded. One possible explanation for this finding is that children were old enough to successfully integrate the visible portion of the wall and the path of the moving ball, making the size of the opening irrelevant. Recall 2-year-olds typically do not show above-chance performance in traditional search tasks, but 3-year-olds do (i.e. Berthier et al., 2000). If performance in Experiment 1 were a function of age,
however, a developmental trend would have been detected. While performance was above chance overall, it was not at ceiling. In fact, on average children could only find the ball half of the time. If they could use even the smallest visual cue (the upper 3cm of the wall) to find the ball, why wouldn’t a larger cue (the fully visible wall) facilitate even better performance?

Children’s above-chance performance indicates that they were focused on a cue that allowed at least moderately successful search. One possibility is that they were focusing only on the wall itself, and not the ball. After all, before the ball appears the wall descends from the top of the screen and comes to rest to the right of one of the doors. This motion might be attention grabbing enough that children remained focused on the wall throughout the trial with no regard for the ball that rolls behind the screen. One post-hoc explanation is that the first seen motion (the descending wall) temporarily narrows the child’s attention to the trajectory of the wall, thus the moving ball is mostly ignored. If so, the correct door is in very close proximity to the child’s field of attention. Indeed, previous research shows that when a cue is near the correct door, children perform quite well (Keen et al., 2008; Shutts et al., 2006). In fact, the descending wall is not the only motion cue that occurs. After the wall is in place, the openings begin to close and expand. It is possible that the ‘movement’ of the openings, further highlights the field of attention along the wall’s trajectory. If the field of attention is narrowed to the entire trajectory of the wall, then the final opening size (i.e. how much of the wall is visible) might not have the expected effect (intersecting the proposed field of attention along the trajectory of the ball).

Does the downward motion of the wall temporarily narrow a child’s attentional field along the wall’s trajectory? If so, it is possible that the motion of the ball and the motion of the wall create two competing sources of information. While one could argue that the two attention-grabbing events- the horizontal trajectory of the ball and the vertical trajectory of the descending wall- might intersect and draw attention to the correct door thereby driving successful
performance, it is more likely that they compete with and/or counteract one another. This could explain why children’s performance is good, but not at ceiling.

The purpose of Experiment 2 was to investigate children’s understanding of solidity and gravity. Within these domains, performance differences are consistently found between violation-of-expectation tasks, manual search tasks and prediction tasks. Each task involves a moving ball that might temporarily narrow a child’s attentional focus to a small area along the ball’s trajectory. If so, information outside of that field of attention becomes peripheral to task performance. Thus when information is provided within the field of attention, performance should be successful.

In Experiment 2, four tasks were presented within each domain: violation-of-expectation, prediction-without-screen, prediction-with-screen and search. The prediction was that when relevant information was visible (during the violation-of-expectation and prediction-without-screen tasks) performance would be more successful than when relevant information was occluded (during prediction-with-screen and search tasks). The order effects in Experiment 2A were resolved by eliminating verbal feedback, so in what follows, I focus on Experiment 2B. The overall results are discussed separately below:

Violation-of-expectation. In the violation-of-expectation tasks, two balls rolled behind a screen. When the screen was lifted, children were afforded a full view of the ramp and the balls, one of which had ‘played a trick’ by violating either the principle of solidity or the principle of gravity. The assumption was that children would perform quite well in the solidity domain because the wall that stopped the ball was not only in full view, it also intersected the proposed attentional field — along the trajectory of the ball. Performance in the gravity domain was predicted to be somewhat less successful in this task, since the gap did not intersect the proposed field of attention. Overall results showed that children could not successfully distinguish between
a ball that has violated a physical principle and one that has not. Traditional violation-of-exception tasks involve a habituation period where the motion of the ball is repeated many times prior to test trials (Spelke et al., 1992), possibly creating a stable field of attention prior to testing. In our case, the ball was only rolled once. It is possible that the change in paradigm resulted in a less salient field of focus and thus, less successful performance than expected.

Another, more likely, possible explanation for children’s poor performance is that they simply did not understand the term “tricky”. After all, the familiarization to the word “tricky” involved a ball dressed like a cowgirl and not to a ball that has violated the laws of physics.

**Prediction-without-screen.** In the prediction-without-screen task, the full apparatus was visible. Children either saw a wall sitting on a ramp or a ramp that had a wide gap along its length. In this task children were asked to predict where a toy dog should stand to catch the ball. The ball did not roll until after the prediction was made. Thus, there was no motion that might draw attention to a particular area of the ramp. The prediction was that children should perform relatively well on this task, because relevant information was in full view. In support of the prediction, results showed that in most cases children were initially quite good, with performance significantly above chance. However, on second trials, performance dropped to chance. These results are quite difficult to explain. One possible explanation is that the lack of verbal feedback was confusing to the child. For example, immediately following the first prediction, the ball was rolled but the children received no verbal response from the experimenter. Then the child performed three more tasks with no feedback before their next prediction-without screen task. The lack of feedback could have confused the child. It’s possible that the children thought the task was being repeated because they were ‘wrong’ the first time. However this assumption contradicts previous research that indicates verbal feedback had no effect on performance
Thus, a closer inspection of tasks that do not involve moving objects prior to the measure of performance is needed.

*Prediction-with-screen and Search.* In prediction-with-screen and search tasks, a screen containing three doors occluded the ramp. Thus, in the gravity domain all of the relevant information was occluded. In the Solidity domain only a small portion of the wall remained visible above the screen. Children either needed to predict where a ball would stop (prediction-with-screen) or which door to look behind to find the ball once rolled (search). Successful performance required the child to use visible cues to guide their search (in the solidity domain this would have been the visible portion of the wall, however, in the gravity domain the relevant information—the gap—was fully occluded). In accordance with the prediction that children would struggle in tasks where 1) a moving object draws attention to an area of the display where relevant information is missing or 2) relevant information is occluded, children struggled to successfully perform the task. These findings are in accord with previous research that show children struggle to find a missing object when attention is focused in an area where no relevant information is available (e.g., Berthier, DuBlois, Poirier, Novak & Clifton, 2000; Hood, Cole-Davies & Dias, 2003; Keen, Berthier, Sylvia, Butler, Prunty, & Baker, 2008; Kloos & Keen, 2005; Mash & Keen, 2003; Mash, Novak, Berthier & Keen, 2006; Perry, Smith, & Hockema, 2008; Perry, Samuelson & Spencer, 2009; Shutts, Keen, & Speake, 2006).

The results of Experiment 2 imply that minimal changes in the task context can drive performance. To what extent could the results be attributed to poor working memory, the ability to keep previous information in mind as new information is coming in. According to Baddeley’s concept of the visuospatial sketchpad, information about object movement and spatial relations is stored for a very short time after the information is received (see Baddeley & Lieberman, 1980, for review). According to this theory, the visuospatial sketchpad does not allow for rehearsal,
making visual and spatial information available only when one can attend to it. Was the poor (and often disordered) performance of children in Experiment 2 related to limited memory capacity? Previous studies suggest the answer is no. In fact, as in Experiment 2 children are often biased by recent events. For example, when an object is hidden in one location multiple times, children can easily retrieve the object (e.g. Smith, Thelen, Titzer & McLin, 1999). They appear to develop a strong ‘memory’ for where the object is. In fact, the effect is so strong that even when the object is hidden in a new location, they continue to search in the original location. This “A not B” error can be reversed, however, by standing the child up or tapping a bar just prior to search (Smith, Thelen, Titzer & McLin, 1999). Such findings imply that an attentional account, and not memory, is a more likely explanation for errors. After all, much like the moving ball in many of the experiments reported above, in the A not B tasks, the child’s attention is temporarily narrowed to the field between their own body and the hidden object. Reaching over and over again to the same location might create a strong attentional field. Thus, unless attention to that field is momentarily disrupted, they will continue to search along that attentional field despite obvious cues that the object is elsewhere.

Overall, the results of this set of experiments highlight how small changes in the immediate context can have a substantial effect on children’s performance. The idiosyncratic differences in performance among tasks and between experiments indicate that performance is clearly not a one-to-one reflection of children's knowledge. Thus, these findings further undermine a core-knowledge approach to children’s problem solving and their ability to make sense of the physical world. Moreover, performance might not be a one-to-one reflection of the task, either. Instead, the results illustrate the intricate interdependence of a multitude of factors and point to the possibility that performance is guided by the moment-to-moment unfolding of task constraints.
and the child’s history. Thus, successful performance depends on the multitude of factors guiding a child’s attention to relevant information.
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