Toddlers' Problem Solving: The Importance of Spatial Integration

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Abstract

While young infants appear competent in some task contexts, older toddlers often show difficulty with the same concepts. They apparently fail to understand something that infants are competent of. Such discrepancy in performance is puzzling, but only if task performance is taken to reflect knowledge or competency. The current study makes a different assumption: Namely that task performance reflects the immediate constraints of the task. We hypothesize that low performance in a conceptually 'easy' task comes from a difficulty with spatially integrating relevant pieces of information. To test this hypothesis, we manipulated the degree of necessary spatial integration in a task that was originally taken to demonstrate toddlers' difficulty with the concept of object solidity. Indeed, toddlers performed better when task constraints were present that minimized the degree to which spatial integration was required. The results point to an important problem in research that seeks to isolate a child's knowledge.

Keywords: toddlers; solidity; constraints;

Introduction

Even the youngest of infants seem to know something about the physical world, about causal relations, about theory of mind, and about the workings of a language (e.g., see Bremner & Fogel, 2001 for a review). Take for example, performance in a physics task. Four-month-olds not only formulate expectations about moving objects that disappear from view (e.g., Baillargeon, 1986), they act surprised when one solid object apparently moves through another (Spelke, Breinlinger, Macomber, & Jacobson, 1992).

Surprisingly however, toddlers fail to draw upon this knowledge in a search task, though it appears to emerge during infancy. For example, when asked to search for a ball that has rolled behind a screen, toddlers cannot use the principle of solidity to search for the ball. They are told on repeatedly that the ball stops at the barrier, and their attention is drawn to the portion of the barrier visible above the screen. Yet, children under 3 years of age fail to search for the ball at the barrier. Instead, they engage in a guessing game, completely ignoring the cue of the barrier provided to them.

Such performance discrepancy between violation-to-expectation tasks and search task has hampered the enthusiasm for approaches that postulate core knowledge (cf., Haith, 1998). How can we claim the existence of core knowledge if children show evidence for such knowledge in some contexts, but not in other contexts?

The current study takes a different approach. Rather than worrying about whether children do or do not know something about a certain concept, we look at general principles of learning: What in the immediate context helps children perform well, and what hinders successful performance? For example, what helps children attend to violations of the solidity principle in a looking task but not in a search task?

Our assumption is that children attempt to link pieces of information into a larger whole, even when it leads to mistakes (cf., Kloos, 2007). For example, if two separate objects move in synchrony back and forth, infants will perceive them to be part of one unified object (e.g., Kellman & Spelke, 1983; Johnson, 2001). Children are likely to link the top and the bottom object into a connected unit. Importantly, such integration may be affected by the spatial distance between events – at least for young toddlers: closer-together events may be more easily integrated than events that are farther apart. Imagine, for example, a ball moving across the diagonal of a plane, say from a front corner to the back corner of a room. For adults, the perception of whether the ball rolls to the back corner of the room, or, instead rises to the top corner of the room is affected by the motion of its shadow (Kersten, Mamassian, Krill, 1997). If the shadow stays in close proximity of the ball, we perceive the ball to move on the floor. But if the shadow moves away from the ball, we perceive the ball to rise to the top. Four-year-olds are affected by the same visual illusion (Kloos, Srivorakiat, Odar, Cummins-Sebree & Shockley, 2007). However, 3-year-olds cannot integrate shadow and ball if the shadow moves away from the ball. They are only able to successfully integrate the proximal cue, but not the more distal cue (Kloos et al., 2007).

In addition to being a relevant factor for perception, is spatial proximity a relevant factor in young children's problem solving? The current study seeks to answer this question for a task that investigates children's thinking about the principle of solidity.

Where is the ball?

Picture a path from left to right that is interrupted by a barrier part way along its path. A ball rolls from left to right and stops at the barrier. Now picture a large screen positioned in front of the path and barrier. The screen is opaque and has four adjacent doors along its lower part. The task is to find the ball by opening one of the doors. Given that the barrier protrudes above the screen, one simply needs to open the door below the visible part of the barrier to find the ball (see Figure 1).

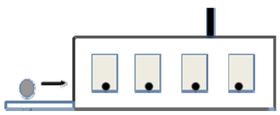

Figure 1: Schematic illustration of the search-task display with the visible portion of the barrier protruding above the screen.

This and similar tasks have been used repeatedly to investigate whether children know that a solid object cannot pass through another, and therefore that the barrier will stop the ball in its trajectory (e.g. Berthier, DuBlois, Poirier, Novak & Clifton, 2000; Mash & Keen, 2003; Hood, Cole-Davies & Dias, 2003; Kloos & Keen, 2005; Shutts, Keen, & Spelke, 2006). Across the board, findings show chance performance in 2.0-year-olds, slightly above chance performance in 2½-year-olds, and consistently successful performance only in 3-year-olds. Rather than taking the barrier into account, 2-year-olds apply a variety of strategies to the search task, with no success: They search for the ball at the location that was correct on the previous trial, they open the same door across trials, or they show a bias for the center most doors (Berthier et al., 2000; Hood et al, 2003; Shutts et al., 2006).

These findings are puzzling because even 4-*month*-old infants understand the principle of solidity. As mentioned above, young infants look longer at a display if the principle of solidity is apparently violated, that is to say, if a ball apparently rolls through a wall. Why would toddlers fail to show the same knowledge in the search task?

Subsequent research found that toddlers – like infants – are surprised by events that apparently violate the principle of solidity (Hood et al., 2003; Mash et al., 2006). Toddlers were presented with the same door display. But rather than asking children to open a door to find the ball, the two doors adjacent to the barrier were opened for them. On physically consistent trials, the ball was resting to left of the barrier. And on physically inconsistent trials, the ball was either missing altogether, or it was resting to the right of the barrier, as if having passed through the barrier. Like infants, toddlers indeed looked longer at physically impossible events than the physically possible events.

Furthermore, 2-year-olds can – in principle – perform a search task. For example, when an object was placed behind one of the doors (in full view of the child) and the child was then asked to retrieve the ball, they could easily open the correct door (Berthier et al., 2000). Similarly, toddlers search correctly when they can track the motion of the rolling object through transparent patches of the screen (Kloos, Haddad & Keen, 2006; Shutts et al., 2006).

Finally, 2-year-olds can reason in advance about how the principle of solidity would affect the motion of the ball barrier (Kloos & Keen, 2005). When the screen was removed and children had to point to where the ball would stop, they correctly predicted that the ball would stop at the barrier. They were successful even when the direction of the ball's motion was changed, or when two barriers (rather than just one) were placed on the ramp. Yet, as soon as the screen occluded part of the ramp and barrier, children failed to take into account the principle of solidity.

The Problem of Integration

Why do children have difficulty to apply their knowledge of solidity when asked to search for the ball by the barrier? One possibility is that children fail to integrate the visible portion of the barrier with the door right below it. Several studies were conducted to test this possibility. For example, in one experiment, the barrier was modified to hang over the front of the screen, such that the entire front edge was visible (Keen, Berthier, Sylvia, Butler, Prunty, & Baker, 2008). In this configuration, the barrier almost touched the door that children should open, decreasing the spatial distance between barrier and door. Yet the majority of toddlers still searched at chance.

Similarly low performance was found when the screen was transparent above the doors (revealing a larger portion of the barrier) *and* the doors were painted in four contrasting colors, each corresponding to a matching barrier (Kloos, Haddad & Keen, 2006). To perform correctly, toddlers simply had to link the barrier to the immediately adjacent door of the same color. Eye tracking results showed that if the child broke eye contact with the ball in motion to look at the barrier, attempts were unsuccessful to locate the ball in its final location.

Finally, even when the barrier was visible through a window in the door, 2-year-olds performed at chance (Shutts et al., 2006). Doors were used that had a window, through which the barrier could be seen. The overlapping proximity between door and barrier minimized the spatial integration necessary. Yet, when no other cue was available, children again failed to open the correct door.

Taken together, these findings further confirm that 2-year-olds pay little attention to the location of the barrier. Toddlers perform poorly, even though they appear to know that the barrier will stop the ball in its trajectory. And they perform poorly, even when the spatial distance between barrier and correct door is minimized. The current study tests an alternative hypothesis, namely that children's low performance is a reflection of their difficulty with integrating the barrier with the motion of the ball (rather than with the door).

Integration of Motion

To perform successfully in the search task described above, children not only have to know about the importance of the barrier in principle, they have to keep in mind that it intersects the path of the ball even after their attention is drawn away from the barrier to focus on the rolling ball on the left of the screen. In other words, they have to keep in mind that something static and distant (the portion of the barrier protruding above the screen) has something to do with the dynamic event (the rolling ball) that happens on the bottom left of the screen. Young children might have difficulty integrating the attention-grabbing motion of the ball with a static cue above the screen, even if they know, in principle, that the ball will come to a halt at the barrier behind the screen. In other words, young children might have difficulty integrating the invisible portion of the barrier with the invisible motion of the ball.

To test this hypothesis, we devised a task in which the barrier was made visible behind the screen without directly showing it behind the screen. We took advantage of a gestalt principle that two separate objects are perceived as a unified object if they move in concert (e.g., Kellman & Spelke, 1983; Johnson, 2001). Applied to the barrier behind the screen, if children see a part of the barrier above *and below* the screen, and the two parts of the barrier move together back and forth, children are likely to perceptually fill in gap between the two parts of the barrier and create a representation of a barrier that intersects the path of the ball. Figure 2 illustrates this principle. Unlike what was done in previous studies, we attempted to integrate the barrier with the ramp – and therefore to integrate the barrier with the motion of the ball. We predicted that children will be able to successfully search for the ball under this circumstance.

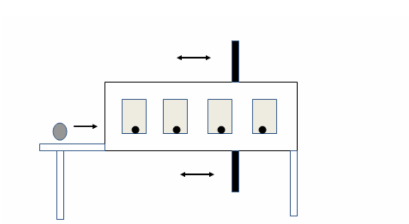

Figure 2: Schematic illustration of the door apparatus when the barrier was visible both above and below the screen, and thus visibly intersected the ball's trajectory.

Experiment 1

The purpose of this experiment was to investigate whether toddlers – given adequate cues – can integrate relevant pieces of information and show improved performance in a task that typically pose serious issues in problem solving.

Method

Participants

Participants were toddlers (*N* = 13) between 25 and 40 months of age (*M* = 2.67 years, *SD* = 3.7 months). Of those 6 were girls and 7 were boys. Four additional children were tested, but were excluded from the study because of experimenter error (one child), or failure to meet participation criteria (see Procedure).

Apparatus

A ramp apparatus with a door screen was used; similar to the one used by Berthier et al. (2000). The ramp was 75cm long and at a slight incline to allow a ball to roll along its full length. The ball was 4 cm in diameter and made out of green foam. A small groove went lengthwise along the center of the ramp to constrain the path of the ball. The screen was an opaque wooden panel (56 cm long and 17 cm wide) that was placed in front of the ramp at all times. It had four doors (each 13.5 cm high and 9.5 cm wide), spaced 5 cm apart from each other. Each door had a knob on the lower part and could be opened easily. Different from Berthier et al, (2000), the ramp apparatus and screen was integrated with a table (60 cm high) such that the area below the ramp was open.

One of two walls was used to stop the ball as it rolled down the ramp, a *short wall* (21.5 cm high and 11 cm wide), and a *long wall (*25.5cm high and 11 cm wide*)*. Each wall had a notch (1.5 cm wide and 9 cm deep) that allowed it to slide back and forth along the ramp and fall into a position on the ramp. With the four-door screen in place, both walls protruded 4 cm above the screen, and the long wall extended 4 cm below the screen.

The experimental program SuperLab was used to randomize the location of the wall for every trial, and to record what door the child opened first.

Procedure

Children were seated in a small chair in front of the ramp table, within reaching distance of the doors. The screen was always in front of the ramp. The experiment consisted of three phases, presented in fixed order: the familiarization, the short-wall phase, and the long-wall phase. The purpose of the fixed order in experiment 1 was two fold: Firstly, we wanted to maximize effect size. Secondly, we wanted to prevent any learning by presenting the long wall first. Each phase consisted of eight trials, presented in random order. Children's task was to "help find the ball" by opening one of the doors. Feedback was given if the child opened the wrong door, and children were allowed to search until they successfully located the ball. However, only the first reach was recorded. Within the eight trials of a phase, the barrier was placed at each of the four doors twice.

During familiarization, the ball was held above one of the doors and lowered directly downward by hand. The experimenter then asked the child to open the door and retrieve the ball. To be included in the final sample, children had to open the correct door on their first try on at least five trials.

Following the familiarization phase, children were asked to walk around to the other side of the table. They watched as the experimenter rolled the ball along the ramp. Next, the short wall was placed on the ramp in the path of the ball. The experimenter demonstrated that the ball stops when it hits the wall. The child then returned to the seat and the short-wall phase started.

For each short-wall trial, the experimenter slid the short wall along the ramp behind one of the four doors Children were reminded that the “ball stops at the wall”, and the visible portion of the wall was pointed out explicitly. This was done to mimic previous studies that provided verbal prompts and feedback (e.g., Kloos & Keen, 2005).

Finally, the short wall was removed and the long-wall phase started. The experimenter placed the long wall on the ramp and pointed out the visible portions of the wall both above and below the screen. After the child acknowledged that he or she could see both parts of the wall, the experimenter slid the wall along the ramp to one of four positions, rolled the ball, and asked the child to search for it. Again, children were reminded on each trial that the ball stops at the wall.

Results and Discussion

The proportion of correct reaches was calculated for each child and each phase. Figure 3 shows the mean proportion of correct reaches per phase, with chance performance being 0.25. During familiarization, when the ball was lowered from above the screen, performance was at ceiling (*M* = .89 *SD* = .13).This was not surprising, given that children merely had to follow the direction of the hand and open the door directly below it (see also *Participants*)

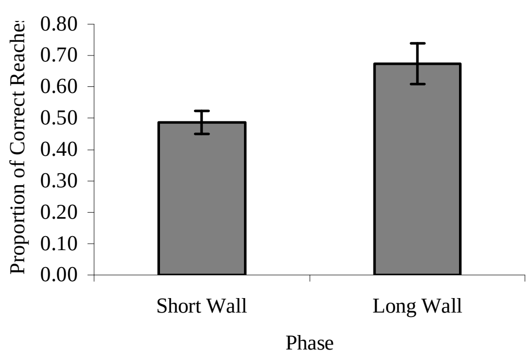

Figure 3: Proportion of correct reaches in Experiment 1, separated by phase. Error bars represent standard errors of the mean. Chance proportion is 0.25

The important result pertains to the difference between short-wall and long-wall phase. A within-group t-test revealed that toddlers searched correctly significantly more often during long-wall trials (*M* =.67, *SD* =.23) than during the short-wall trials (*M* = .48, *SD* =.23), $t(12) = 3.51$, $p < .05$. While search during both phases was above chance (assuming chance probability of 0.25, short wall: $t(12) = 3.24$, $p < .05$), many more children performed above chance in the long-wall phase than in the short-wall phase (7 vs. 1 children performed correctly in at least six out of the eight trials, binomial probability $p < .05$). These findings indicate that the long wall (and the tandem motion of the two visible portions) did in fact allow successful integration of barrier and ball motion. Our findings in the short-wall trials are consistent with previous findings for this age group even though these previous studies did not use the verbal prompt before each trial (e.g., Berthier et al., 2000).

Experiment 2

Is it possible that children performed better in the long wall trials due to training effects? The long-wall phase followed the short-wall phase, and children might have performed better in the second phase simply because they were getting better over time. The purpose experiment 2 was to rule out that the findings in experiment 1 reflect practice effects. In experiment 2, children were never presented with the long wall during trials. Rather, they were given eight familiarization trials, eight short wall trials followed by eight additional short wall trials. Any improvement in the second set of short-wall trials would speak for training effects.

Method

Participants

Participants were toddlers (*N* = 12) between 24 and 40 months old (*M* = 2.6 years, *SD* = 3.9 months). Of those, 6 were girls and 6 were boys. Two additional children were tested, but were excluded from the study because of experimenter error (one child), or failure to meet participation criteria (see Procedure).

Apparatus

The same apparatus was used in this experiment. However, only the short wall intercepted the path of the moving ball.

Procedure

The procedure was identical to experiment 1, except that rather than switching to the long wall during the third phase; the short wall was again used during the last eight trials.

Results and Discussion

Figure 4 shows the proportion of correct reaches per trial. Again, children searched near ceiling during familiarization (*M* =.85, *SD* =.13). And during the first set of short-wall trials, performance did not differ from performance of short-wall trials in experiment 1 (*M* = .40 vs. *M* = .48, respectively).

The important result pertained to children’s performance during the first and second set of short-wall trials. A within-group t- test revealed that performance during second set of short-wall trials (M = .42, SD = .16) was not significantly different from performance during the first set of short-wall trials (M = .40, SD = .16), ($t(11)$= .67, p > .05). In fact, only three children (25%) searched correctly more often during the second than the first phase. In experiment 1, there were nine children (70%) who improved from short-wall to long-wall phase. In other words, there was no improvement across trials that could result from feedback and experimenter prompts. This suggests that improved performance in experiment 1 during long-wall trials cannot be explained with prolonged experience with the apparatus.

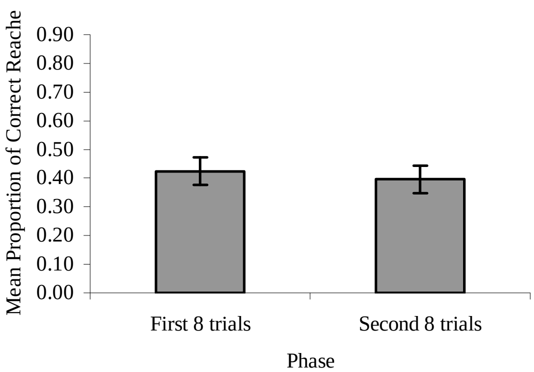

Figure 4: Proportion of correct reaches per trial during experiment 2, separated by phase. Error bars reflect standard errors of the mean. Chance performance is 0.25.

General Discussion

Our study was set out to reconcile a puzzling incongruity between a search task and a violation-of-expectation infant-looking task, both of which require seemingly similar knowledge about the physical world. The knowledge that underlies both types of tasks pertains to solidity, the knowledge that solid objects take their own space in time, and thus cannot pass through each other. Previous findings show lower performance in the search task than in its complimentary violation-of-expectation task: Children appear surprised when the principle of solidity is violated, but this knowledge does not guide their search.

Our hypothesis was that children's success depends on the degree to which integration of relevant pieces of information is supported in the immediate task context. In this task, we argued that the relevant pieces of information pertained to (1) the trajectory of a ball rolling behind a screen, and (2) a barrier intersecting that trajectory. In support of our hypothesis, we manipulated the degree to which the barrier was perceived to intersect the trajectory of the ball. Indeed, 2-year-olds performed better in the condition in which the barrier apparently intersected the ramp (long-wall trials) than in the condition in which this was not the case (short-wall trials). Our findings show that two visible portions of the wall moving in tandem above and below the screen were crucial for successful performance. Toddlers search correctly for the ball behind the screen nearly 70% of the time. Experiment 2 ensured that these findings were not due to simple learning effects.

One could argue that the long wall merely highlighted the correct door: A barrier extending below and above the screen might ease a spatial integration of the barrier and the door behind which the ball can be found. However, previous findings speak against this possibility. Despite rather obvious measures of decreasing the spatial distance between barrier and correct door, children's search performance did not improve (e.g. Keen et al., 2008; Kloos et al., 2006; Shutts et al., 2006). Our results suggest, instead, that the long wall highlighted the intersection of barrier and ramp, and thus highlighted the principle of solidity for children. It is possible that the lower portion of the long wall, in such close proximity to the ramp, was enough to improve performance. Future studies could address this issue by dividing the short wall trials into separate upper wall and lower wall conditions.

Note that nothing in the display gave away the answer about the position of the ball. Our manipulation merely made the intersection of ramp and barrier more obvious, and as such potentially helped children apply their knowledge of solidity to this task. However, it is also possible that the highlighted intersection between barrier and ramp grabbed children's attention and led them to open the door at that intersection, with little regard to the physical principle of solidity. After all, the experimenter reminded the child on every trial that the ball stops at the barrier. It was therefore not necessary for children to independently employ any physical knowledge about solidity. One might question why the children were reminded that the ball stopped at the barrier. Previous results reveal that this verbal prompt elicits no improvement in performance (Kloos & Keen, 2005). Further, the purpose of this study was not to explicitly test children's knowledge of object solidity. Therefore, our results do not speak directly to the question of whether toddlers know something about solidity, or whether they can form expectations about hidden events.

Instead, our results underscore a fact that is often overlooked: namely that performance is never merely a reflection of the child's knowledge. Our findings further lend support to the argument that a child's performance reflects a conglomerate of constraints that operate in the immediate task context, constraints that help or hinder integration of the relevant pieces of information (e.g., Smith, Thelen, Titzer & McLin, 1999; Van Orden, Pennington & Stone, 1990). Our findings show that scaffolding the integration of the pertinent cues resulted in remarkable improvement of performance.

It is possible that performance, whether that of a young infant, toddler, or an adult, never demonstrates a certain knowledge, or lack thereof. Instead, it demonstrates the coordination of events, a coordination that is either mistaken from the experimenter's point of view, or it is appropriate. Along the same lines, it is possible that even the violation-of-expectation looking paradigms fail to demonstrate certain knowledge (or the lack thereof). Instead, it might demonstrate the degree to which scaffolding constraints guide children's attention to coordinate events in one way or another. If so, it would be important to better understand the kinds of the constraints that operate at different age groups – rather than the kinds of knowledge that is present in different age groups. For example, what is it that interrupts successful coordination in a task in which the ball falls (Hood, Carey & Prasada, 2000), rather than rolls, even though both tasks used long-wall trials?

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