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PAPER

Conflicting cues in a dynamic search task are reflected in children's eye movements and search errors

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Abstract

Three-year-olds were given a search task with conflicting cues about the target's location. A ball rolled behind a transparent screen and stopped behind one of four opaque doors mounted into the screen. A wall that protruded above one door provided a visible cue of blockage in the ball's path, while the transparent screen allowed visual tracking of the ball's progress to its last disappearance. On some trials these cues agreed and on others they conflicted. One group saw the ball appear to pass through the wall, violating its solidity, and another group saw the ball stop early, behind a door before the visual wall. Children's eye movements were recorded with an Applied Science Laboratories eye tracker during these real object events. On congruent trials, children tended to track the ball to the visible barrier and select that door. During conflict trials, children's eye movements and reaching errors reflected the type of conflict they experienced. Our data support Scholl and Leslie's (1999) hypotheses that spatio-temporal and contact mechanical knowledge are based on two separate, distinct mechanisms.

Introduction

Spatiotemporal information has proved to be a powerful factor in investigations of infants' knowledge about objects. In Kellman and Spelke's seminal study of 4-month-olds' response to object unity (1983), observing common movement of top and bottom sections of an object whose middle was occluded proved to be more effective than shape or color in signifying unity. At 10 months of age infants used spatiotemporal information, but not featural information, to infer the existence of occluded objects (Xu & Carey, 1996). In Scholl and Leslie's theory of the infant's object concept (1999), the authors distinguished between object knowledge based on spatiotemporal information and that based on contact mechanics, suggesting the two types of knowledge systems 'may be subserved by specific and distinct mechanisms'. Contact mechanical knowledge is based on information about object properties such as solidity and how objects interact with one another. Spatiotemporal knowledge is based on visual tracking and involves an attentional mechanism called object indexing that keeps track of an object's location as it moves about (Leslie, Xu, Tremoulet & Scholl, 1998; Pylyshyn, 1994). Most relevant to the data presented here is their prediction that the spatiotemporal aspects of object indexing would be 'cognitively impenetrable'. In other words spatiotemporal information would be accepted, more or less uninfluenced by top-down information. In contrast they cited instances of contact mechanical knowledge influenced by new information about object properties.

This distinction makes sense in the everyday world. If you see a ball roll behind a screen and not emerge, you do not need to know its color, weight, or texture to infer that it is probably behind the screen. If you look for it at the point of its disappearance, there is a good chance that you will find it. On the other hand, to predict whether a barrier will stop an object moving toward it, one needs to know the object's weight and force relative to the strength of the barrier. Certainly the infant's world is replete with spatiotemporal information as movement of people and objects is observed from the very beginning of life. Untold opportunities exist for the infant to observe complete and partial occlusions, disappearance and reappearance of objects with accompanying sound, continuity of an object's movement from one place to another, and so on. This is not to say that infants do not have plentiful opportunities to observe events based on contact mechanical principles. Rather the point is that object properties (e.g. weight) and outside forces (e.g. gravity) are liable to influence such events to a greater extent, and this knowledge is constantly expanding (e.g. having learned that most objects fall to the floor rather than float, the infant then sees a balloon which appears to violate the gravity rule). It follows from this distinction that compared to contact mechanical knowledge,

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spatiotemporal knowledge might accrue earlier in development and possibly would maintain a certain primacy in later development.

In addition to the support provided by Scholl and Leslie (1999) for their theory of two separate knowledge systems, the work of Hood (1995), Hauser (2001), and Santos (2004) offers compelling evidence. Hood (1995) found that 2–3-year-olds make an odd error in a search task that he termed the 'gravity error'. The apparatus consisted of three opaque tubes connecting three holes at the top with three boxes at the bottom. The task was to find a ball dropped into one of the holes, and the solution seems obvious: follow the attached tube to the box connected to it below. This task is simple for the child if the tube goes straight down, but if the tubes are crisscrossed, children choose wrongly. In Hood's study they ignored contact mechanical information fully visible in the tube display, and chose the box directly below the hole where the ball was dropped. They appeared to rely on their past experience with spatiotemporal information from objects falling straight down, hence the gravity error. They persisted in this mistake even when shown the correct answer on each trial. Using a food drop task, Hauser (2001) found that rhesus macaques also made the gravity error if a screen blocked their view of an apple falling into a cup on a shelf. They looked for the apple under the shelf. If the screen was removed and they could see the apple drop into the cup on the shelf, they made a correct retrieval.

This dissociation in rhesus macaques' ability to use spatiotemporal information but not contact mechanical information was extended by Santos (2004) in a series of studies that support the notion of two separate systems, and also suggest that spatiotemporal knowledge may be more basic or primitive than contact mechanical knowledge. Santos (2004) reported that rhesus macaques readily solved a search task when the cue to the hidden location was spatiotemporal information, but not when contact mechanical information was provided. A plum was rolled down a ramp and stopped behind a near or far panel. In this task spatiotemporal information was the horizontal movement of an object rolling behind and between the occluding panels, so disappearance without reappearance marked the hiding place. In the contact mechanical task a wall, visible above a screen, stopped the object's progress, but a screen hid the object's movement between panels. When the screen was removed, the sight of the wall's top above one panel was the only cue to which panel hid the object, and the macaques were unsuccessful just as in Hauser's task. Santos (2004) proposed a dissociation between the two knowledge systems, with macaques capable of using one type of information but not the other. She connected this dissociation in non-human primates with data from children that showed they have more success with problems that rest on spatiotemporal knowledge than those requiring contact mechanical knowledge.

Search tasks that depend on contact mechanical knowledge have proven to be very difficult for 2–3-year-old children (Berthier, DeBlois, Poirier, Novak & Clifton, 2000; Hood, Carey & Prasada, 2000; Mash, Keen & Berthier, 2003). In these tasks an opaque screen covered an object's movement and the cue to where to search was a partially visible obstruction in the object's path (top of a vertical wall in Berthier and Mash's horizontal apparatus, and edges of a horizontal platform in Hood *et al.*'s vertical apparatus). When the Berthier *et al.* (2000) task was subjected to a critical analysis (Keen, 2003; Keen & Berthier, 2004), it became clear that many steps are necessary to solve this problem. The child must recognize the top of the barrier as a cue to where the ball stopped, must spatially integrate the separate elements of wall, ball, and door to predict the ball's exact location, and use this knowledge to guide an action plan that leads to opening the correct door. Not until 3 years of age do children solve this problem reliably (Berthier *et al.*, 2000).

When spatiotemporal information was added to this search task, performance improved only slightly in 2-year-olds, but substantially in 2.5-year-olds (Butler, Berthier & Clifton, 2002; Kloos, Haddad & Keen, 2006). In the original study the opaque screen hid the ball's trajectory soon after it was released (Berthier *et al.*, 2000). In Butler *et al.* (2002) and Kloos *et al.* (2006) a transparent screen was used, with only the doors made opaque. Intermittent glimpses of the ball's movement between doors and the failure to emerge from behind the door with the wall provided new information about the ball's hiding place. This spatiotemporal information proved sufficient to raise 2.5-year-olds' performance to a high level. If they tracked the ball's progress to its final disappearance, they opened the correct door about 85% of the time, compared to around 35–40% when the barrier was the only cue (Berthier *et al.*, 2000; Mash *et al.*, 2003). In these studies chance was .25 because there were four possible doors to open.

The evidence for infants' and young children's attention to spatiotemporal information is strong. For example, the large literature on number indicates that infants keep track of how many objects disappear and reappear from behind a screen, confirming their attention to object movements in relation to occlusion (Wynn, 1996). Likewise, Spelke's studies of continuity of movement (reported in Spelke, 1988) showed infants' sensitivity to objects' movements between or behind two occluders. The use of eye-tracking technology has enabled us to measure how well infants can follow objects in and out of occlusion. Gredeback and von Hofsten (2004) reported that infants between 6 and 12 months of age could anticipate when and where an object would appear after occlusion when the object was moving on a circular trajectory. Scott Johnson and colleagues have examined infants' eye movements in studies of object unity involving occlusion (Johnson, Slemmer & Amso, 2004) and representation of linear motion behind an occluder (Johnson, Bremner, Slater, Mason, Foster & Cheshire, 2003). The eye-tracking literature supports the notion that human infants are highly attentive to moving objects undergoing occlusion;

they follow moving objects with their gaze and anticipate reappearance.

In spite of abundant evidence for infants' attention to spatiotemporal information, we have been unable to find studies that tested how their experience and expectations might be influenced by top-down knowledge. In light of Scholl and Leslie's suggestion that spatiotemporal information might be cognitively impenetrable, we devised an experiment that put these two types of information into conflict. In Butler *et al.* (2002) and Kloos *et al.* (2006) the cues of the barrier and non-emergence from behind a door were always congruent, and thus supported the same conclusion about the ball's whereabouts. By using a transparent screen, the spatiotemporal cue of disappearance and the contact mechanical cue of the barrier can be congruent or placed in direct conflict. Because 3-year-olds can search successfully using the barrier as a cue when the screen is opaque, it was assumed that they would perceive the conflict between the two cues.

The cues were decoupled in two ways, only one of which violated the principle of solidity. Solidity conflict was produced by having the ball apparently roll through the visible wall and then stop two doors after the wall. If children had a strong expectation that the wall would stop the ball, they might disregard the violation and choose the door by the wall. We predicted, however, that the perceptual act of visually tracking the ball would be powerful enough to overcome their initial assumption. The second manipulation had the ball stop two doors before the visible wall. A more subtle physical principle was violated, inertia, in that a moving object should continue to move unless obstructed. However, this principle also involved knowledge of frictional force between the ball and the track, and these are not so easily discernible. We expected that children would have a strong assumption that the ball would stop at the visible barrier, which would lead them to overlook the failure to reemerge from behind a previous door. On the other hand, if children were simply tracking the ball's movement, disappearance after occlusion would lead them to open the correct door. Specific errors of opening the door associated with the wall are critical in trying to determine children's understanding of this problem.

To summarize, we hypothesized that children in both conflict conditions would weigh the spatiotemporal cue of disappearance more heavily than the contact mechanical cue of solidity for three reasons. First, the former cue is more direct, not requiring knowledge or reasoning about solidity. Second, compared to contact mechanics, spatiotemporal information appears to be used earlier in children's development and by adult macaques in search tasks. Finally, in our conflict situation it is also the more valid cue. In other words, if the ball emerged from behind the door with the barrier, one should not search at that door. Likewise, if the ball failed to emerge from behind a door without the barrier, one should open that door rather than the door with the barrier. Choosing spatiotemporal information over expectations based on contact mechanics will always be reinforced on conflict trials. By making the spatiotemporal cue the more valid, we weighted the events to give the hypothesis of cognitive impenetrability the best possible chance of confirmation. If indeed spatiotemporal knowledge is not malleable in the face of disconfirming information, children were expected to rely on it almost exclusively. To the extent that they rely on their knowledge of contact mechanics to reason about the ball's location, they will err. If mistakes are made initially but learning occurs as trials progress, this would suggest that both spatiotemporal and contact mechanical knowledge are subject to top-down input.

Because correct tracking was closely linked to successful behavioral outcomes in the transparent screen task (Butler *et al.*, 2002), eye gaze was recorded in the present study. We hypothesized that heightened attention to the wall would predict errors of opening the door associated with the wall, whereas correct tracking (keeping the eye on the ball) would predict correct choices. In this study we attempted to use the coordination between choice behavior and eye movements to explicate the underlying cognitive processes in a search task. This study was unique in two ways: it combined detailed analysis of sequential eye movements with search behavior to illuminate the process by which a cognitive conflict got resolved, and it tested how children weigh spatiotemporal information in conflict with contact mechanical information to solve a search task.

Methods

Participants

Potential participants were identified from state birth records. A recruitment letter was then sent to parents followed by a phone call. Fifty 3-year-old children (age range 2 years, 11 months, 13 days to 3 years, 1 month, 5 days) were recruited for this study. Children were randomly assigned to the Stop-Early group or the Violation-of-Solidity group (described in the procedure). One child was dropped from the final sample due to an experimenter error, leaving $n = 25$ in the Violation-of-Solidity group and $n = 24$ in the Stop-Early group. Parents were required to sign an informed consent form after the study was explained according to university procedures. The internal review board approved the study protocol and informed consent form.

Apparatus

The apparatus used was similar to that in Butler *et al.* (2002). In all trials four opaque doors were mounted into a transparent screen that was placed in front of a wooden ramp. A barrier whose top was always visible above the screen was placed behind one of the four doors (Figure 1a). The apparatus was designed so that

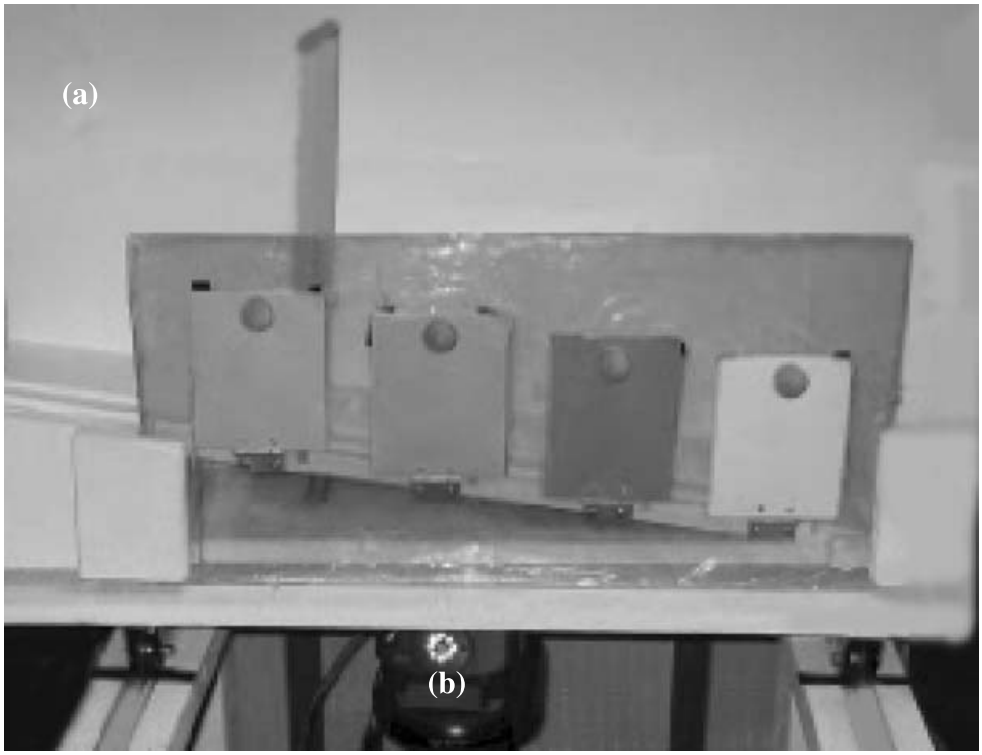

Figure 1 *(a) Apparatus used in experiment. A ball is rolled down the ramp and is stopped by a barrier behind one of the four doors. After the ball comes to a stop the apparatus is pushed forward and the child is asked to find the ball. (b) ASL eye camera used to track the point of gaze for each subject.*

the screen could be removed between trials and the child could see the whole ramp. In the trials where the cues of emergence and solidity were placed into conflict, the ball was stopped by a small Plexiglas barrier invisible to the child (further described below). A Styrofoam ball was rolled down the ramp, from left to right, on every trial. The ball was padded so that no sound was produced when the barrier stopped the ball. The approximate rolling time from the top of the ramp to the end was 1.2 seconds. The ball was visible to the child between each of the opaque doors for approximately 0.25 sec.

The apparatus was placed on a custom-built table (Figure 1a). Tracks were placed on the sides of the table so the apparatus (on wheels) could easily be pushed towards the child after the rolling event. During the rolling event the apparatus was pulled back (approximately 95 cm) from the child to prevent premature door opening and to accommodate recording of eye movements. The child's point of gaze was recorded during the rolling of the ball using a corneal reflection eye-tracking system manufactured by Applied Science Laboratories (Model 504). An Ascension Technologies magnetic position tracker was attached to the ASL system. The magnetic tracker monitored the child's head movements so that the eye-camera could maintain an eye image despite head movements. The eye-camera was placed under the apparatus to record an unobstructed eye image during the rolling event. When the apparatus was pushed forward to allow the child to open a door, the apparatus obstructed the eye-camera, and no valid eye data were recorded. Valid eye data thus only existed for the rolling phase of each trial and not when the child was opening a door.

An additional camera (not part of the ASL setup) was mounted above the ramp apparatus facing the child. This camera was positioned so that head and body movements of the child could easily be monitored. This camera was helpful to assess reasons for losing the eye image (e.g. the child was not looking at the apparatus or the head moved out of range). The video signals from the ASL control box and from the camera facing the child were recorded simultaneously onto a Sony DV video deck using a picture-in-picture video mixer.

Procedures

Two experimenters were required in this study, one experimenter (E1) to interact with the child during the experiment and a second experimenter (E2) to control the eye-tracking system. The child sat on the parent's lap throughout the whole testing session. The magnetic tracking sensor was mounted into a headband and placed above the left eye of the child before the session began.

During familiarization the ramp apparatus was placed within reaching distance of the child. A small puppet was then lowered behind each of the four doors and the child was asked to find the puppet. The apparatus was then pulled back out of reach and the rolling-ball event

was demonstrated. The screen was removed and a barrier was placed on the ramp. The child was then shown how the ball rolled down the track and stopped at the barrier. For each of the four positions E1 commented: 'Look, the ball stops at the wall', a procedure used in previous studies with this task (Berthier *et al.*, 2000; Butler *et al.*, 2002).

Before beginning the test trials, the eye-tracking system was calibrated so that an accurate point-of-gaze measurement could be attained. Typical calibrations for the ASL corneal reflection system require that the subject look at nine known points in space, these points are then entered into a computer software program as the subject systematically looks at each point. Previous eye-tracking work has been done on 2-D computer displays, enabling the researchers to show the children highly colorful and animated calibration points at which to look (Aslin & McMurray, 2004). In the current setup a real object display was used and we found that 3-year-old children lost interest when asked to systematically look at nine known points in space. We thus calibrated the eye-tracker to an adult eye prior to the child entering the lab. Previous work found that calibrating to an adult eye and then customizing the calibration to each child using a linear offset would yield eye data accurate to the spatial resolution necessary to assess point of gaze on the doors and ball during the rolling event on the apparatus (Kloos *et al.*, 2006). The linear offset was done by having E1 activate a hand-held puppet within the child's view. Assuming the child was looking at the puppet, E2 then offset the recorded point of gaze so that it exactly matched the real location of the puppet. After the linear correction was performed, E1 moved the puppet around the calibrated area to ensure that the calibration was accurate. If the calibration was not accurate then it was redone. If it appeared that the child's eye could not be calibrated to the adult calibration file the child's point of gaze data were not analyzed.

After the familiarization and calibration phase was concluded the test trials were initiated. A total of 12 test trials, divided into three blocks of four trials, were administered. The beginning of each test block was devoted to checking the accuracy of the eye image. E1 held the puppet behind the screen slightly above and between the two middle doors, and encouraged the child to look at the puppet. As in the calibration phase, E2 manually centered the recorded eye image onto the puppet if necessary. A check followed in which E1 moved the puppet behind the screen to various locations and E2 ensured that the cursor (the child's calculated point of gaze) followed the puppet.

Between each trial a decorated poster board was placed in front of the apparatus so that the child could not see the experimenter placing either the visible barrier or piece of Plexiglas on the track. The decorated poster board also helped maintain a stable eye image and yield more reliable eye data because it kept the child's attention focused in the region of the apparatus between trials.

To test the hypothesis that spatiotemporal information was cognitively impenetrable, children needed to see that both cues were initially valid. Thus, children could rely on whatever cue they were inclined toward when they entered the lab and be correct. Subsequently the contact mechanical cue became invalid; this abrupt change allowed us to determine which cue they were using. Learning was assessed by measuring performance over 12 intermixed congruent and conflict trials. The first block of trials (trials 1–4) consisted of congruent trials for children in both conditions. The ball was rolled down the ramp and stopped out of sight behind the door by the barrier, or wall. Within these four trials the barrier was placed once at each of the four doors, with the order determined randomly.

The second block of trials (5–8) consisted of conflict trials in which the ball was stopped by a small 2 cm piece of Plexiglas, behind one door. The Stop-Early group saw the ball stop two doors before the barrier whose top was visible above the screen. Specifically, when the barrier was placed at door 3 the ball stopped behind door 1 and when the barrier was at door 4 the ball stopped behind door 2. The Violation-of-Solidity group saw the ball stop two doors beyond the visible barrier. When the barrier was placed at door 1, the ball stopped behind door 3 and when the wall was placed at door 2 the ball stopped behind door 4. For these trials a different wall (but identical in appearance) was used that had a hole at the bottom so the ball would roll through it and continue until stopped behind the door by the small piece of Plexiglas. The hole in the visible wall was never seen by the child.

The last block of trials (9–12) was a mix of congruent and conflict trials, with the first two (trials 9 and 10) being congruent and the last two (trials 11 and 12) being conflict, for a total of six congruent and six conflict trials. In this last block of congruent trials, for both the Stop-Early and Violation-of-Solidity groups, the ball only stopped at doors 3 and 4. Because there were only two trials in this second block, it was not possible to balance the trials among all doors and we wanted to make the congruent trials as similar as possible between the two groups. Only two trials were collected for the last two congruent and conflict trials because it had been observed in previous research (Berthier *et al.*, 2000) that children of this age typically perform 12 trials or fewer before they lose interest in the task.

Data analysis

Two experimenters scored the door the child opened for each trial. There was 100% agreement between the two scorers regarding these behavioral data. Eye movements were analyzed by scoring the cursor that identified point of gaze from the digital videotape that was recorded from the eye-tracking system. In the congruent trials, eye data were scored for sequential eye fixations during the rolling event. Eye fixations on the apparatus were defined as the eye stopping on one of the four doors or

the wall for at least five digital video frames (approx 170 ms). The eye data were then categorized based on the sequence of eye fixations during the rolling event. Eye data were categorized as correct tracking if the child exhibited sequential fixations at each of the doors before terminating at the door where the ball stopped. Other sequences of eye fixations were categorized as incorrect tracking. Scoring the congruent data in this manner allowed us to confirm the findings of previous studies that found that children above 2.5 years tend to track the ball down the apparatus to the correct door and then open the correct door (Butler *et al.*, 2002).

In the conflict trials, a more in-depth analysis of eye movements was employed. In these trials we were primarily interested to see if the child's eye behavior was related to subsequent choice of door. Point of gaze was assessed in relation to the ball's position during the rolling event. Criteria appropriate to the ball's differential movements in the two groups were applied to define correct tracking. In both cases the child had to witness the ball's disappearance by tracking it within ± 100 ms of the moment it rolled behind the correct door. In the Stop-Early group the eye had to either pause for at least $\frac{2}{3}$ of a second when the ball disappeared, or scan no more than one door past where the ball failed to emerge and immediately return to the previous door. Two-thirds of a second represented a conservative number to define the pause necessary to ensure that the children in the Stop-Early group understood that the ball had stopped progressing down the ramp (given that the ball disappeared behind each door for 250 ms). In the Violation-of-Solidity group the eye had to continue to track the moving ball beyond the wall. Incorrect tracking was most often due to focusing on the wall by saccading to the door by the wall without tracking, or looking back at the wall immediately after tracking. All other eye behavior was categorized as inattentive, defined as eye movements that did not appear to be influenced by either the rolling ball or the visible wall. The point of gaze data for each conflict trial were defined as belonging to one of these three categories (correct scan, incorrect scan and inattentive), which were then related to the behavioral performance on the task. Two coders scored the point of gaze data. The primary coder scored 100% of the data and a secondary coder scored 33% of the data. There was 95% agreement between the two coders.

Out of the final 49 children, reliable eye data were obtained for 36 children (17 in the Stop-Early group and 19 in the Violation-of-Solidity group). In the Violation-of-Solidity group eye data were lost in six children due to the children refusing to wear the headband ($n = 2$), excessive movement of the child ($n = 1$), the inability to detect a stable corneal reflection or pupil centroid ($n = 2$) or other miscellaneous system failures ($n = 1$). In the Stop-Early group eye data were lost in seven children due to the children refusing to wear the headband ($n = 2$), excessive movement of the child ($n = 3$), the inability to detect a stable corneal reflection or pupil centroid ($n = 1$) or experimenter errors ($n = 1$). Reliable eye data was defined as a session where at least eight of the 12 trials had a stable cursor and point of gaze could be adequately determined.

Results

Behavioral data

The behavioral data are reported for all 49 children, including those from whom eye data were lost. To check for position biases, the number of times children chose each door (regardless of whether it was correct or not) is shown in Table 1. Also reported in Table 1 are the frequencies that each door was correct, along with the proportions representing the number of times children chose a correct door over the number of times that door was actually correct. A proportion greater than 1.0 indicates that children chose the door more often than it was the correct choice, whereas a proportion less than 1.0 indicates that the door was correct more often than it was chosen. All numbers are close to 1.0 on congruent trials, indicating that no strong position bias was present for any door initially. On conflict trials the effect of disagreement in visual information can be seen, causing door choice to be spread more unevenly among the four doors, but again no position bias was obvious.

In the congruent trials, the proportion of correct doors opened was .78 (111/142) and .71 (98/138) in the Violation-of-Solidity and Stop-Early group, respectively. Performance suffered in both groups when the emergence and solidity cues were placed into conflict. For these trials, the proportion of correct doors opened was .60 (88/146) and .46 (64/138) in the Violation-of-Solidity and Stop-Early group, respectively. A two-way mixed

Table 1 *The frequency of opening each door for all congruent trials, Violation-of-Solidity conflict trials and Stop-Early conflict trials. The first number in each cell indicates the number of times that particular door was chosen. The second number in each cell indicates the number of times that particular door represented the correct choice. The final number in each cell indicates the proportion between the number of times the door was chosen over the number of times the door was correct*

	Door 1	Door 2	Door 3	Door 4
Congruent	53 | 46 = 1.15	45 | 46 = .98	92 | 95 = .97	90 | 94 = .96
VS conflict	6 | 0 = NaN	9 | 0 = NaN	45 | 72 = .63	84 | 72 = 1.16
SE conflict	46 | 68 = 0.68	46 | 67 = 0.69	19 | 0 = NaN	24 | 0 = NaN

ANOVA (groups by trial type) revealed no differences between the two groups ($F(1, 47) = 1.65$; $p > .21$), but performance was better when cues were congruent than when they were in conflict ($F(1, 47) = 24.73$; $p < .0001$), indicating that many children chose to open a door not based solely on spatiotemporal knowledge.

Analysis of the type of errors made revealed that contact mechanical knowledge exerted a powerful effect on children's choices, but this was influenced by the type of conflict trials they experienced. Children in the Violation-of-Solidity group chose the door by the wall for only 16% of their total errors; their most frequent error was to open the door adjacent to the correct door. In contrast, the Stop-Early group chose the door by the wall on 61% of their total errors on conflict trials. This group difference was highly significant ($t(1, 47) = 26.44$, $p < .001$). At the same time overall error rates for the two groups were comparable ($t(1, 47) = 2.05$, $p > .16$). The children who saw a clear violation of solidity (i.e. the ball apparently rolled through the wall) were more likely to disregard the visible wall as a barrier that would stop the ball. The Stop-Early group who never saw this violation tended to choose the door by the wall that fit their expectations based on contact mechanical knowledge. They opened this door despite spatiotemporal information that the ball never reached that door.

Learning effects were examined by looking at the first two versus the last two trials in each of the trial types (see Figure 2). For congruent trials, the early trials consisted of trials 1–2 and the later trials consisted of trials 9–10. For conflict trials, the early trials consisted of trials 5–6, and the later trials consisted of trials 11–12. Only the first two trials of the congruent and conflict block one were chosen so that the number of trials in the analysis matched the number of trials in the second block. A three-way mixed-design ANOVA, 2 (group) × 2 (trial type) × 2 (trial block), revealed – in addition to the predicted effect of trial type ($F(1, 47) = 18.42$; $p < .0001$) – a significant effect of trial block ($F(1, 47) = 4.49$; $p < .05$). Learning was apparent in that mean performance on the later trials (last block of congruent and conflict trials) was significantly above performance on early trials (first block of congruent and conflict trials). There was no significant interaction and no post-hoc comparisons were significant.

Large individual differences were found in the data for both groups. The median proportion correct was over .8 on congruent trials in both groups (Figures 3 and 4). Children in both groups tended to score well above chance, with several being correct on all trials when the emergence and solidity cues agreed. The conflict trials presented a larger challenge. In both groups the range of the data expanded to cover all possibilities, with only four children choosing correctly on every trial, while three never chose the correct door. The median in both groups fell to about .5. The large group variability indicates that when the two visual cues about the ball's location were in conflict, a few children realized that the visible wall was no longer a valid marker, whereas most children did not. We examined each child's performance to see if it exceeded what would be expected by chance over both the congruent and conflict trials using a binomial distribution with a rejection region of .05. In the congruent trials, the number of subjects scoring above chance was 19/25 and 16/24 in the Violation-of-

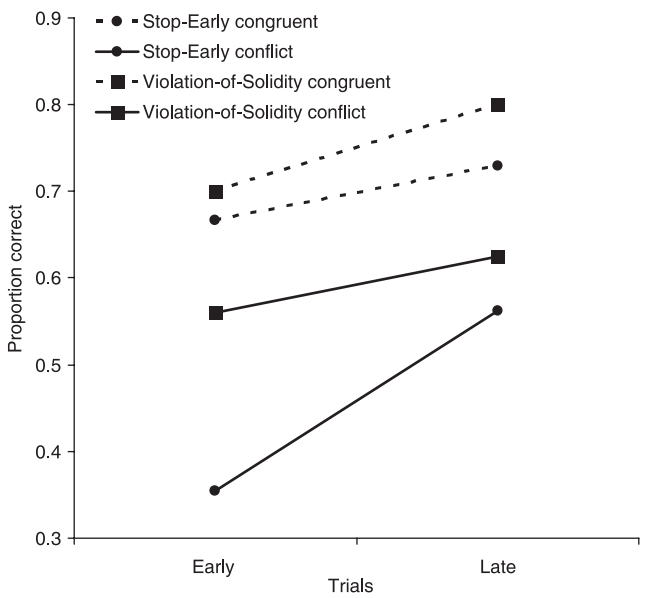

Figure 2 *Proportion correct of the early congruent and conflict trials versus the late congruent and conflict trials.*

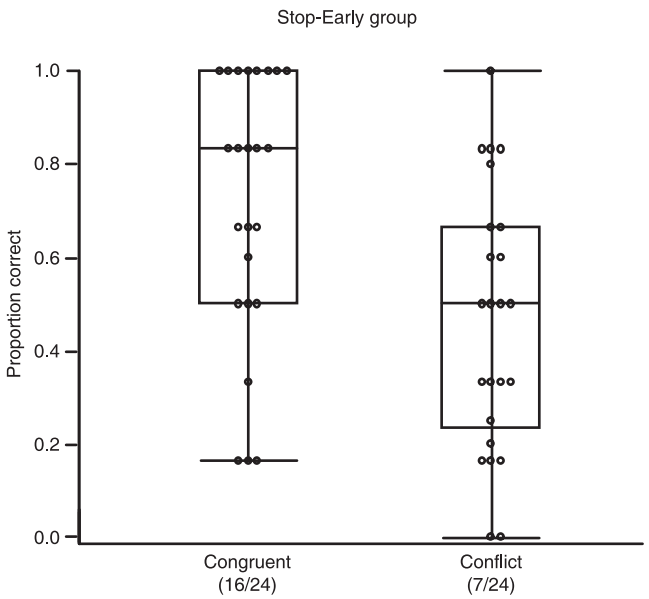

Figure 3 *Box and whisker plot for the Stop-Early group. The box encompasses the central 50% of the data, while the whiskers show the range. The line in the center of the box is the median value of the data. The circles superimposed on the plots are the individual data points representing each child. The numbers in parentheses represent the number of children that scored above chance using a binomial distribution with a rejection of .05.*

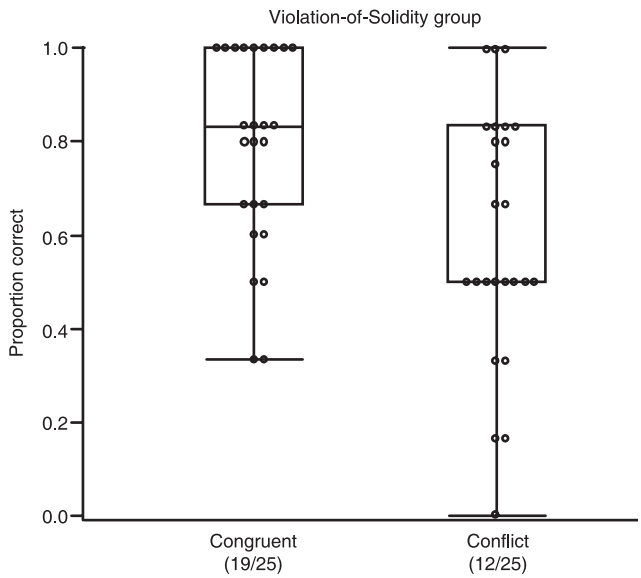

Figure 4 *Box and whisker plot for the Violation-of-Solidity group. The box encompasses the central 50% of the data, while the whiskers show the range. The line in the center of the box is the median value of the data. The circles superimposed on the plots are the individual data points representing each child. The numbers in parentheses represent the number of children that scored above chance using a binomial distribution with a rejection of .05.*

Solidity and Stop-Early group, respectively. In the conflict trials, the number of subjects scoring above chance was 12/25 and 7/24 in the Violation-of-Solidity and Stop-Early group, respectively.

Eye data for congruent trials

By coordinating eye movements with behavioral data we attempted to understand the cognitive processes underlying performance. We need to emphasize that tracking behavior during the rolling ball event need not match looking behavior during the act of opening a door. Tracking behavior occurred 2 to 3 seconds before the act of opening a door because the apparatus was positioned out of reach during the rolling ball event (see Method). The eye-camera was occluded when the apparatus was pushed forward to allow door opening, so there is no record of where children were looking during the moment of reaching for a door. Most probably children were looking wherever they were reaching, correct or incorrect, because children generally look where they are reaching. The value of eye data during the rolling event is that it may reflect the decision-making process during the time when critical information for a correct response was provided. Eye data can tell us if the child observed this critical information and behavioral data can tell us if the child used this information to make a choice.

Eye data for the 19 children in the Violation-of-Solidity group included 114 congruent trials (six per subject), with 16 trials dropped because no door was selected (n = 1), the eye image was lost (n = 8), excessive noise in the eye data (n = 3) or the child peeked around the apparatus to see the ball (n = 4). Eye data for the 17 children in the Stop-Early group included 102 congruent trials, 18 of which were dropped because no eye image was obtained (n = 9), excessive noise in the system (n = 2), the child peeked (n = 6), or the child opened two doors (n = 1). Children in both groups saw the same events on congruent trials, that is, the ball's motion coincided with the presence of the wall. Use of either or both cues would lead to opening the correct door, and as expected children were correct most of the time (142/182, or 78% of trials), about the same as in the entire sample (see Behavioral data).

To determine if correct door choice was preceded by correct or incorrect tracking, an ANOVA was performed on groups (2) × type of tracking (2). Only the effect of tracking was significant ($F(1, 34) = 81.95$, $p < .001$). For both groups correct tracking and fixating on the door by the wall was followed by choosing the correct door over 90% of trials. When an incorrect door was chosen, no tracking effects were observed ($F(1, 34) = .1$, $p > .05$). This response was preceded about equally by correct and incorrect tracking. The meaning of the relation between tracking and door choice on congruent trials is somewhat ambiguous because one cannot determine which cue they were using, but these figures do furnish a baseline for children's eye behavior when cues are not in conflict. Only on conflict trials can eye behavior discriminate between attention to movement versus attention to the barrier.

Eye data for conflict trials

For the Violation-of-Solidity group, the ball would always pass through and stop two doors after the visible barrier. In this group there were 100 trials with valid eye data out of a possible 114. Fourteen trials were dropped because of excessive noise in the system or an unexplained loss of an eye image (n = 10), the child peeked around the apparatus before opening a door (n = 2) or the child refused to open a door (n = 2).

In conflict trials for the Stop-Early group, the ball would always stop two doors before the visible barrier. There were a total of 80 trials with valid eye data out of 102 total in the conflict Stop-Early group, with 22 trials dropped because of excessive noise in the system or unexplained loss of an eye image (n = 12), the child was not looking during the rolling event (n = 3) or the child peeked to find the ball before selecting a door (n = 7).

To determine if correct door choice was preceded by correct or incorrect tracking, an ANOVA was performed on groups (2) × type of tracking (2). As in congruent trials, the groups did not differ, with only the effect of tracking significant ($F(1, 34) = 28.88$, $p < .001$). Correct door choice was preceded by correct tracking on 76% of trials (81/106). Even on trials that featured correct tracking, children nevertheless paid attention to the wall. Examples of this are shown in Figure 5. In the Violation-of-Solidity

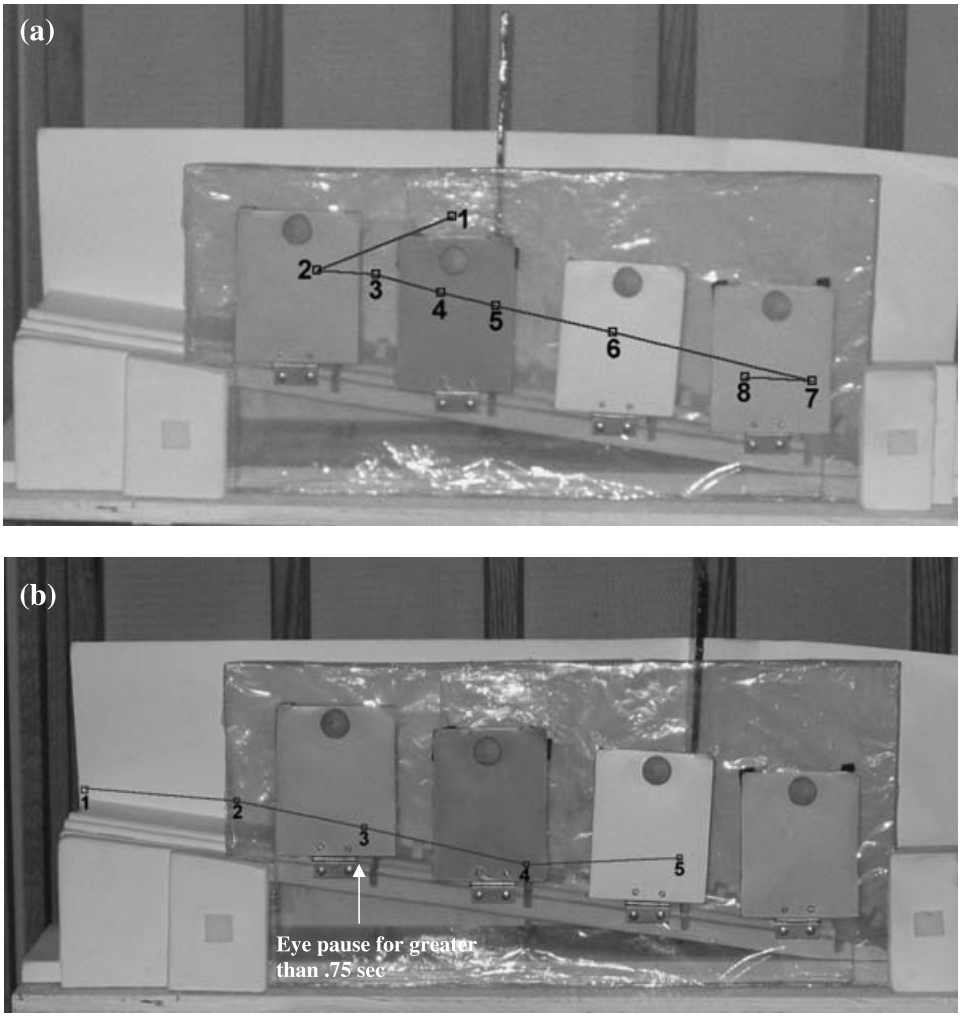

Figure 5 *Eye-scan path representing the typical correct pattern in (a) a Violation-of-Solidity trial, and (b) a Stop-Early trial. The numbers represent sequential eye fixation points. In (a) the ball is behind door 4 and in (b) it is behind door 1.*

group the dominant eye movement pattern was to follow the ball down the ramp until it disappeared (see Figure 5a); this pattern had the advantage of direct foveal fixation on the correct door when the ball stopped. In this trial the child first looked at the wall then followed the ball down the ramp until the ball disappeared behind door 4. Although the child tended to linger at the door with the wall (identified by the double fixation points on door 2) the child nevertheless correctly tracked the ball past the wall to the point of disappearance. A correct scan path for a child in the Stop-Early group is shown in Figure 5b. The eye tracked the ball and made a lengthy pause when it stopped behind door 1. Although this was the door the child eventually opened, the eye followed a path to the door by the wall, suggesting that this door was also considered.

Because correct tracking preceded correct door choices on 76% of those trials, it was important to establish that this eye pattern was not dominant on all trials, including trials when an incorrect door was chosen. Of the total incorrect trials, correct tracking occurred on 35% (26/74), with incorrect tracking being the dominant scanning pattern on these trials. This difference was significant ($F(1, 34) = 4.33$, $p < .04$). Incorrect tracking in both groups caused the child to miss the event of the ball stopping to roll, but the scanning patterns were different. A typical incorrect scanning pattern is shown in Figure 6a for a child in the Violation-of-Solidity group. The eye stayed at the wall door (fixations 2, 4, and 5) before a saccade to door 3, then door 4. The child then opened door 4 although the ball stopped at door 3. In this type of error children seemed to assume the ball was going to stop at the wall. When they noticed that the ball (probably in peripheral vision) apparently rolled through the wall, children then looked at doors further down and typically opened one of them. Rarely did this group open the door by the wall, limiting their choice to the two doors past the wall.

A typical incorrect scanning pattern for a child in the Stop-Early group is shown in Figure 6b. Here the critical event of ball disappearance is missed because the eye made a saccade directly to the door by the wall. Although this saccade was followed by looks back to previous doors, including the door where the ball was hidden, the

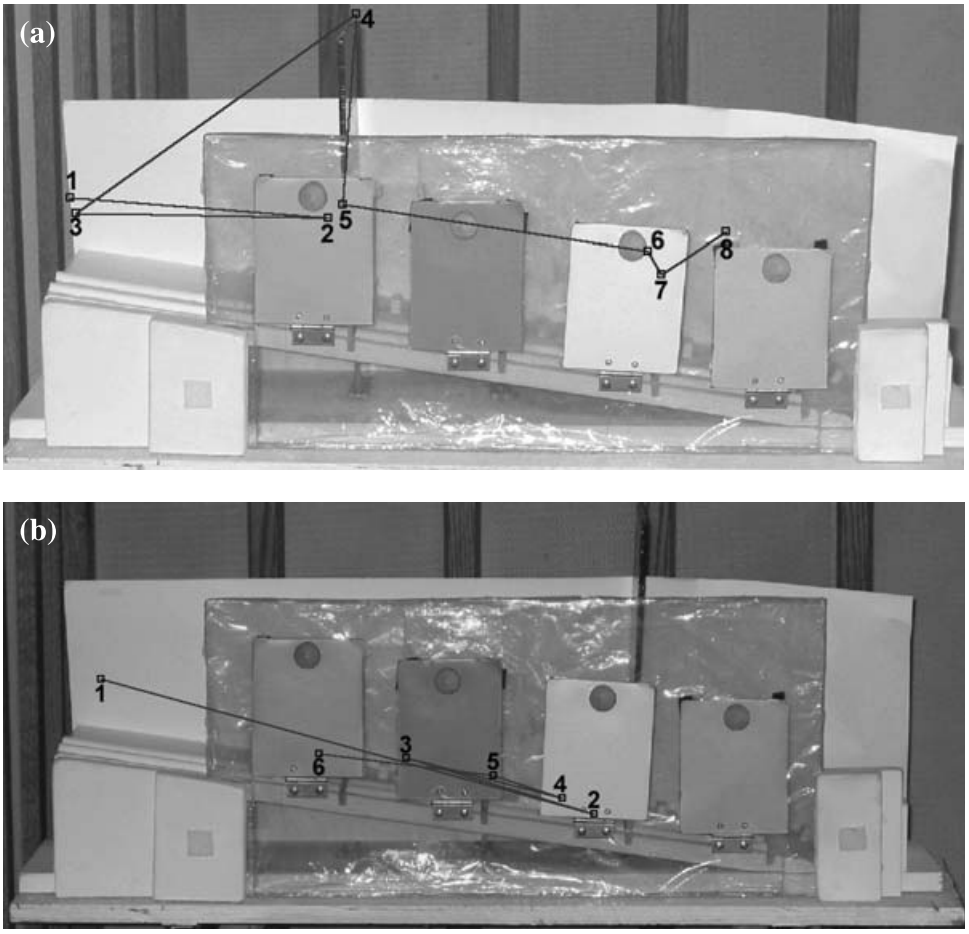

Figure 6 *Eye-scan path representing the typical incorrect pattern in (a) a Violation-of-Solidity trial and (b) a Stop-Early trial. The numbers represent sequential eye fixations. The ball is behind door 3 in (a) and door 1 in (b).*

child eventually chose the visible wall door. As noted in the statistical analysis of errors in the behavioral data section, for this group the most typical error was to choose the door by the wall.

Discussion

Three-year-old children were presented with a search task in which they had to find which of four doors a rolling ball had stopped behind. In a previous version of this task (Berthier *et al.*, 2000), the ball's progress was hidden behind an opaque screen and the only way to determine where it had stopped was to notice the top of a barrier protruding above one door. In the present study the screen was made transparent, with only the doors opaque, so that the ball's movement was a salient cue, as well as the barrier. With this arrangement, reasoning about solidity (i.e. the wall stops the ball, so it is behind the door by the wall) could either be congruent or put into conflict with the spatiotemporal cue of the ball's movement and final disappearance. We judged this latter cue to be more primitive, not requiring any reasoning about the juxtaposition of two objects and their interaction, as does contact mechanical information. Furthermore, because we made the place of last disappearance the most valid indication of the ball's location, it should trump any reasoning about the role of the barrier. By recording eye movements in conjunction with search behavior, we hoped to gain insight into how children might weigh these cues that rest on different knowledge bases.

Children were first given trials where the two cues agreed. On these congruent trials they were able to find the ball a high percentage of the time (about 75%). Eye movement data for both groups showed that the dominant strategy was to track the ball to the visible barrier and then select that door. Correct tracking virtually assured success, resulting in correct choice of door on over 90% of those trials. Butler *et al.* (2002) also found that when the cues of disappearance and solidity were congruent, younger children aged 2.5 years were able to select the correct door when they watched the ball's disappearance.

As expected, performance dropped when cues were placed into conflict. The lower performance on conflict trials leads us to infer that children made some use of both cues when they agreed. If they relied solely on contact mechanical knowledge about the effect of the wall, performance on conflict trials should have fallen to chance.

If they were using spatiotemporal information solely, performance should have stayed near or equal to that on congruent trials as the efficacy of this cue did not change across trial type. Neither of these patterns dominated, so we conclude both cues were probably used when they were available and congruent.

The large individual differences seen in Figures 3 and 4 suggest that some children may have engaged in extreme reliance on a single cue. Four children had 100% performance on conflict trials but only two of these were also perfect on congruent trials. These children either never relied on contact mechanical information to indicate the correct door, or came immediately to ignore it when cues were put into conflict. It is also difficult to interpret the other extreme pattern, near-chance performance on conflict trials. Poor performance could result from reliance on contact mechanical information or from inattention to any cue.

The eye data support the interpretation that children were weighing both cues. For conflict trials, correct tracking was defined in terms of attention to the ball's movements, whereas incorrect tracking was defined as focusing on the wall. We assumed that attention to the wall door reflected children's expectations about contact mechanics. Success on conflict trials reflected children's preference for movement cues over the wall cue. As we predicted, the spatiotemporal cue came to dominate on conflict trials as children learned its validity over time, but the contact mechanical cue was never completely abandoned. This finding agrees with Scholl and Leslie's (1999) interpretation that contact mechanical cues are constantly updated by new incoming information; when the wall proved to be an unreliable cue, it tended to be discounted. On the other hand, our data do not agree with their speculation that spatiotemporal information is 'cognitively impenetrable'. Children did not always choose the door where the ball disappeared, but continued to be influenced by their expectation that the door with the wall was the correct door, even in the face of clear evidence that this was not the case. We interpret 3-year-olds' attention to the wall as evidence of their knowledge of solidity and contact mechanics. This knowledge exerted a powerful effect on door choice. Even correct tracking did not guarantee that children would subsequently open the correct door. Whether tracking was correct or incorrect, both types of cue continued to exert influence. The different pattern of errors for the two groups, however, suggests that the type of conflict event observed determined the process of how contact mechanical cues came to be disregarded. The group who saw the ball apparently roll through a solid wall and out the other side came to quickly ignore the visible barrier. The sight of the ball's continuation down the track refuted their assumption that it would stop at the door by the wall. Eye-tracking data confirmed this interpretation. Children in this group did not stop tracking the ball at the visible wall and open that door. Scanning usually continued to doors beyond the visible barrier and even when they were highly attentive to the barrier, they rarely opened that door. Fixations on the wall are strong evidence that this group considered opening the door by the wall, but ultimately rejected it. For these children spatiotemporal information overcame any assumptions about the wall stopping the ball and their attention became rightly focused on the ball's movement.

Children who saw the ball stop behind a door before it reached the door with the visible barrier had a different problem. Even though they may have paused at the door where the ball failed to emerge, they subsequently kept scanning on toward the visible wall. Their most typical error was to open the door with the barrier, and this error was preceded either by an initial saccade to that door or by looking back and forth among several doors before finally going with the barrier door. For this group making a correct choice entailed giving up the assumption that the ball would stop at the barrier, as it had during congruent trials. Without a direct visual disconfirmation, children fell prey to this assumption, causing a drop from .67 correct on early congruent trials to .35 on early conflict trials. As trials continued and the ball was not found behind the door with the barrier, children learned to weigh the cue of non-emergence more, so that by the end of conflict trials they improved to .56 correct, not significantly different from the group who experienced a violation of solidity.

In conclusion, when solving a dynamic search task 3-year-old children seem to use both cues provided by their knowledge of contact mechanics and spatiotemporal information contained in the object's movement. When the cues were placed into direct conflict, children re-evaluated the information from each cue. We had predicted that the ball's disappearance would exert a more powerful effect than the contact mechanical cue when these cues conflicted. This was supported most clearly by children continuing to perform well when only spatiotemporal cues proved valid. There appears to be a developmental progression with regard to these two types of cues. Children of 2.0 years of age rarely look at the wall and make only occasional use of spatiotemporal information in a similar search task (Kloos *et al.*, 2006). Children of 2.5 years of age use spatiotemporal information but not contact mechanical information (Berthier *et al.*, 2000; Butler *et al.*, 2002). The earlier emergence of spatiotemporal information and the use of contact mechanical information by 3-year-olds in this study lend strong support to Scholl and Leslie's (1999) claim that knowledge based on spatiotemporal and contact mechanical information arises from 'specific and distinct mechanisms'. By relating the pattern of behavioral errors to the accompanying eye movements we were able to distinguish the influence of each system.

Finally, in most studies of spatial reasoning and object search, cues that children might use are studied in isolation. Location coding, use of landmarks, place learning, and motor learning have all been studied individually. In *Making Space*, Newcombe and Huttenlocher (2000, p. 38) noted that 'little attention' has been directed toward

how children weigh competing spatial information. In the current study we sought to separate the influence of spatiotemporal and contact mechanical cues by placing them in conflict. This strategy could also be used to look for developmental changes in other aspects of spatial reasoning.

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