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Which cues are available to 24-month-olds? Evidence from point-of-gaze measures during search

Heidi Kloos, Jeffrey M. Haddad, Rachel Keen *

Department of Psychology, University of Massachusetts, Amherst, MA 01003, USA

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Abstract

In previous research 2-year-olds have failed to show knowledge of solidity in a search task in which a ball rolled behind a screen and was stopped by a barrier. The screen had four doors and the barrier was visible above the door hiding the ball. To establish what cues 2-year-olds might be using, precise point-of-gaze measures were taken during the hiding event. A transparent screen with opaque doors provided two cues: (1) the ball could be tracked until it failed to emerge, and (2) the barrier's position could indicate the correct door. Point-of-gaze measures revealed that children failed to use the more indirect cue of the barrier, which requires reasoning and spatial integration. Their search success was predicted only by the more immediate cue of actively tracking the ball. These findings support the claim that children use best those cues directly related to the object's disappearance, while failing to use cues that entail higher cognitive demands.

Keywords: Eye tracking; Visual search

A well-documented finding about young children's physical knowledge is that different tasks yield different success rates (cf., Chen & Siegler, 2000). A prominent example in the literature pertains to children's knowledge about solidity, that is, knowledge that solid objects cannot pass through one another. While children, and even young infants, show knowledge of solidity in a violation-of-expectation task (Hood, Cole-Davies, & Dias, 2003; Spelke, Breinlinger, Macomber, & Jacobson, 1992), they fail to show this knowledge in a search task (Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Hood, Carey, & Prasada, 2000).

Both kinds of solidity tasks (the violation-of-expectation task and the search task) involved a moving ball, a barrier that stopped the ball, and a screen that concealed the event of the rolling ball while leaving the upper portion of the barrier visible. In the violation-of-expectation task, the screen was lifted after the ball came to a stop. It revealed the ball either resting by the barrier (consistent event) or where it appeared to have passed through the barrier (inconsistent event). Infants and 2-year-olds looked longer at the inconsistent than at the consistent event, suggesting that they expected the ball to stop at the barrier (Hood et al., 2003; Spelke et al., 1992). In the search task, the screen was left in front of the display and children were asked to find the ball by opening a door in the screen. To perform correctly, children have to open the door by the barrier. Yet toddlers' fail this task (Berthier et al., 2000; Hood et al., 2000). Even

* Corresponding author. Tel.: +1 4135452655; fax: +1 4135450996.
E-mail address: rachel@psych.umass.edu (R. Keen).

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though they seem to understand the relevance of the barrier in a ball's trajectory (cf., Kloos & Keen, 2005), children do not open the door by the barrier.

Requirements for the two tasks differ in a number of ways. The motor act of reaching in the search task is more complex than the mere viewing of the display required in the violation-of-expectation task, but this difference is unlikely to fully account for the discrepant findings (Keen, 2003). By 2 years of age, children have had substantial experience with reaching for an object, and they can perform the motor act of opening the correct door when the location of the object is obvious to them (Baker, Klitzing, & Keen, 2005).

On the other hand the search task places additional cognitive demands on the child. In the violation-of-expectation task, the screen was lifted to reveal the ball's position, so the child must only recognize whether "something is amiss" to use Diamond's (1998) words. Conversely, in the search task, the screen was left in place and children had to link the portion of the barrier visible above the screen to the correct door. Given that the barrier is physically separated from the correct door, children must spatially integrate these two parts to determine the ball's correct hiding place. Children's failure to solve the search task may lie in their difficulty of integrating the barrier with the correct door (Keen, 2005).

Young children's ability to spatially integrate a cue with a hiding location is indeed rather limited (DeLoache, 1986). DeLoache (1986) presented 21- and 27-month-olds with four unique containers. When an object was hidden in one of the containers and they were rearranged, children could find the object. When four identical containers that could be distinguished only by a cue placed on top of them were used, 27-month-olds but not 21-month-olds, performed above chance. In this arrangement children had to integrate the cue with the hiding container, a task that proved difficult for the younger children.

Eye movements may offer a way to assess whether visual integration might be taking place. If children look at the barrier, track the ball's movements, and engage in scanning between the barrier and the door where the ball disappeared, one could conclude that the child attempted to visually integrate the critical elements of the hiding event. If children do not look at the barrier, do not track, and do not scan between elements of the display, this would suggest they are missing information that would help them solve the problem. By measuring eye movements accurately and relating those data to search performance, we hoped to distinguish between what was observed and what was used to solve the problem.

In a study with 2-year-olds (Butler et al., 2002) eye movements were scored crudely from videotape and revealed that younger children usually tracked the moving ball. If they broke their gaze away from the correct door before opening it, however, most often they opened an incorrect door. This strongly suggested that 2-year-olds were not using the barrier as a cue. From the videotape data we could not determine if the children ever focused on the barrier itself. In the current study we sought to determine how eye movements throughout the hiding event might be related to search performance.

We also attempted to facilitate children's search performance in two ways. A screen was used that was partially transparent so that the ball was visible as it rolled between the opaque doors. In order to open the correct door, children simply had to track the ball as it rolled between the doors and open the door where it last disappeared. No reasoning about the barrier's role was needed. To further aid children in their attempt to spatially integrate the barrier and the correct door, the doors were painted unique colors with each barrier matching to the corresponding door in color. To perform correctly, children had to simply open the door with the same color as the barrier visible above the door. While children still needed to integrate the barrier with the correct door, having matching colors between barrier and corresponding door seemed likely to enhance such integration. In previous studies the doors were identical and the barrier had a contrasting color that may have emphasized the physical separation of cue and hiding place.

1. Method

1.1. Participants

Participants were twenty-one 2-year-olds (seven girls and fourteen boys) with a mean age of 24 months and 1 week (range = 23 months, 2 weeks to 25 months). Fifteen additional children were tested and dropped from the sample because of equipment failure ($n = 8$), failure to obtain reliable eye-data on at least eight trials ($n = 4$) or lack of the child's interest in participating ($n = 3$). While this attrition rate is high compared to studies with infants that use procedural measures, it is not unusual for studies that use eye-tracking measures, given the rather complex technical equipment.

1.2. Visual display

The ramp apparatus used was similar to the one used in Butler et al. (2002). Fig. 1a shows a schematic of the ramp apparatus used. Four barriers could be inserted along a wooden ramp at 30.5, 44, 57.5, or 71 cm from the top of the ramp. A transparent Plexiglas panel with four opaque doors served as the screen. Each door covered the intersection between a barrier and the ramp. A Styrofoam ball could be rolled down the ramp (total rolling time: 1.2 s), and was visible for approximately 0.25 s between adjacent doors. The doors had unique colors (blue, orange, red, or pink) and were matched in color with the corresponding barriers. The color of a particular door/barrier pair was counterbalanced for position along the ramp among children. The solid squares in the figure represent the nine points used for calibration (Fig. 1a).

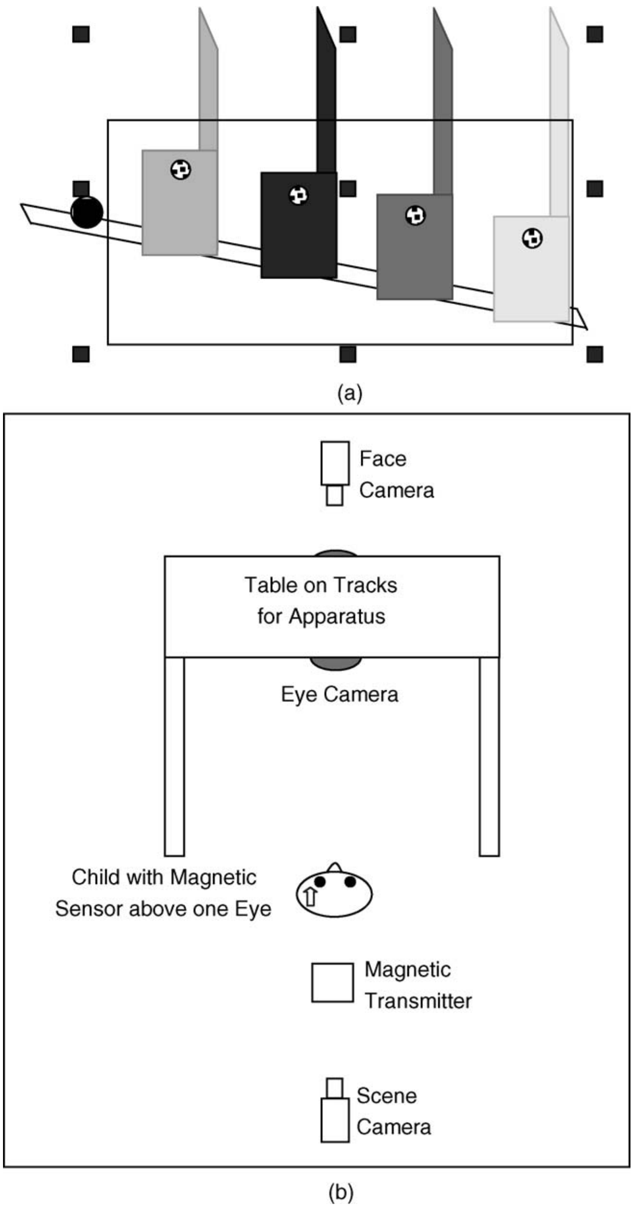

Fig. 1. Schematic illustration of the equipment. (a) Ramp apparatus with the partially transparent door panel showing all four barriers, each matching in color with the corresponding door. Note that during actual trials only one barrier was in place. The solid squares denote the nine-point matrix used for calibration. (b) Arrangement of the ramp apparatus and eye-tracking equipment.

1.3. Eye-tracking set-up

A corneal reflection eye tracking system in association with a head tracking system (Applied Science Laboratories Model 504) was used to track children's eye movements at 60 Hz (see Aslin & McMurray, 2004 for a description of this system). Fig. 1b shows the arrangement of the equipment from an overhead view. The door apparatus was placed on tracks and could be moved either out of a child's reach (at a far position 95 cm from the child), or within a child's reach (so the child could open a door). The eye-tracker was mounted below the apparatus at the far position. It recorded a child's point-of-gaze during the hiding event (Fig. 1b).

A scene camera mounted behind the child recorded the image of the door apparatus. This image was integrated in the control box with the image of the eye camera to produce the child's point-of-gaze (displayed as a small black cursor) superimposed on the image of the scene camera. A face-view camera mounted above the door apparatus recorded the child's head movements and reaching behavior when asked to open a door. A video mixer allowed a small image of the child's head to be displayed with the scene camera image of the video monitor. The head image was helpful during trials where the eye image was lost to determine why the image dropped out (i.e., excessive head turn, blink, a hand in the way, or system error).

While eye movement analyses are frequently used to explore perceptual and cognitive processes (see Aslin & McMurray, 2004), these methods have been limited largely to infants looking at 2D computer displays, where calibration points can be highly colorful and animated. In this study, precise eye movement of toddlers needed to be obtained using a real object display. Toddlers, unlike infants, become bored quickly and find it difficult to sit still through the calibration procedure necessary to obtain precise eye-movement measures (i.e., 9-point calibration). To circumvent this problem, we created a 9-point calibration file with an adult participant and used it with children. Pilot testing showed that an adult calibration file provided precise eye movement measurement without a lengthy experimental procedure for the child. The nine points of the calibration matrix spanned the ramp apparatus from left to right of the ramp and from the top of the barriers to the level of the eye camera, as shown in Fig. 1a. The calibration file obtained for the adult was loaded into the interface at the start of the experimental session. To ensure that the adult calibration provided correct mapping of a child's point-of-gaze, each participant in the current study was asked to look at various positions at the beginning of the experimental phase. Testing began only after the child's calculated point-of-gaze matched with the location that the child was asked to look at.

1.4. Procedure

Two experimenters were needed for this experiment. One experimenter (E1) interacted with the child and created the events visible to the child. The second experimenter (E2) was responsible for obtaining a stable image of the child's eye. The child was seated on the parent's lap in front of the ramp apparatus. A headband with the magnetic sensor was placed on the child's head in such a way that the sensor was above the right eye or between the two eyes (the right eye was always the tracked eye).

During an initial warm-up phase, the ramp apparatus with door panel was placed within reaching distance from the child. Four trials were presented (one at each of the four doors) in which a small finger puppet (5 cm high) was lowered by hand behind one of the doors, and the child was asked to find it by opening the respective door. The apparatus was then pulled backwards, above the eye camera. The door panel was removed and a barrier was placed on the ramp. In four trials (one for each position of the barrier) the child was shown how the ball rolls down the track and stops at the barrier. E1 commented: "Look, the ball stops at the wall."

The next phase was devoted to obtaining a stable eye image of the child. E1 held the puppet at the middle position of the 9-point calibration matrix (between the two middle doors of the door panel, see Fig. 1a). The child was encouraged to look at the puppet while E2 manually centered the eye camera on the child's eye and then switched the eye camera to the automatic mode of operation. A cursor appeared on the monitor (the child's calculated point-of-gaze) superimposed on the image of the scene camera. A check followed in which E1 moved the puppet to various locations, and E2 ensured that the cursor followed the puppet. If the cursor did not coincide with the puppet (probably due to differences in relative separation of corneal reflection and pupil centroid between the child's eye and the adult calibrated eye), a linear offset was performed (provided by the eye tracker software): The child was asked to look at the middle position while E2 adjusted the position of the cursor manually by pressing the respective key on the keyboard. The linear offset provided a correction for the calculated point-of-gaze so that it corresponded to the actual point-of-gaze.

Three blocks of four testing trials followed. For each trial, a barrier was placed on the ramp, and the door panel was placed in front of it. The child's attention was directed towards the position of the barrier and then towards the ball at the start of the ramp. Once the child looked at the ball, the experimenter rolled the ball down the ramp. After approximately 1 s, the apparatus was pushed within reaching distance of the child, and the child was asked to open the door to find the ball. When the apparatus was pushed forward to allow the child to open a door, the eye camera was obstructed and no valid eye data was recorded. Valid eye data thus only existed for the rolling phase of each trial and not when the child was opening a door. If the child did not open the correct door at the first attempt, E1 encouraged the child to open another door until the ball was found. Each of the four barriers was used once within a block of four testing trials. No order of four trials was repeated for a child. If children were willing to continue with the game ($n = 5$), an additional trial was completed to replicate and replace a previous trial where the eye image may have been lost.

After each block of four testing trials, the accuracy of the child's eye image was assessed. E1 moved the puppet to various locations behind the door panel. If the cursor representing the child's point-of-gaze did not coincide with the location of the puppet, linear offset was performed again by E2 in the same manner as described above.

2. Results

A trial was coded as correct or incorrect depending on whether the child opened the correct door at the first attempt. If the child opened two doors at the same time, and neither of them revealed the ball, the trial was coded as incorrect. If one of the two doors was correct, the trial was coded as not usable ($n = 2$). The primary scorer scored all the data, and a secondary scorer scored half of the participants, with inter-rater reliability of 100% agreement. A proportion correct score was calculated for each child (the mean number of trials completed by each child was 12.1). The mean obtained ($M = 0.36$, S.D. = 0.19) was significantly better than would be expected by chance (assuming a chance probability of 0.25, $t(20) = 2.78$, $p < 0.02$), and comparable to children's performance in Butler et al.'s (2002) transparent-screen task ($M = 0.39$). The distribution of scores in comparison to Butler et al. (2002) and Berthier et al. (2000) is displayed in Fig. 2. There was a significant main effect of group ($F(2,54) = 4.85$; $p < 0.01$), and a Tukey post hoc test revealed that

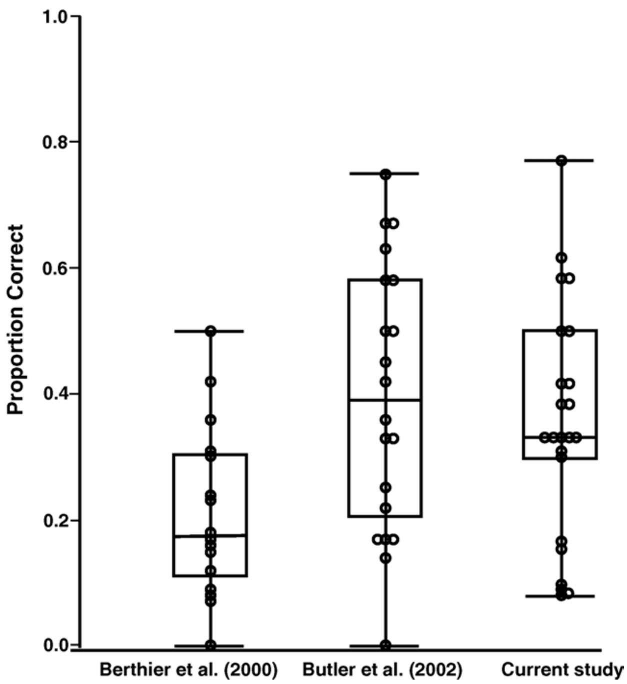

Fig. 2. Proportion of trials in which each child correctly retrieved the ball in the current experiment. The distributions of scores obtained in Butler et al. (2002) and Berthier et al. (2000) are given for comparison purposes. The distributions are plotted within box-and-whisker plots, where the boxes enclose the second and third quartiles of the distribution. The horizontal lines in the boxes are the medians.

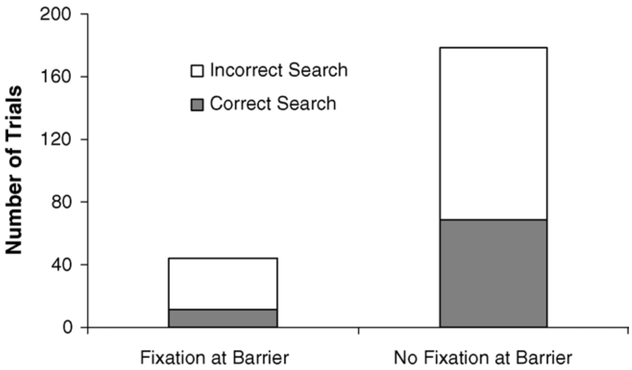

Fig. 3. Number of trials in which children did or did not fixate at the barrier. The shaded areas show the number of trials in which children opened the correct door in each category.

improved performance with a transparent screen (Butler et al., and the current study) is significantly better than the performance from the opaque screen used in the Berthier et al. study ($p < 0.05$).

2.1. Children's fixations at the barrier

Thirty-five trials (out of 257) could not be coded due to excessive noise in the eye movement (10 trials) or failure to obtain a stable eye image (25 trials). The average number of scored trials for each child was 10.5. Children's data were discarded from the final sample if fewer than eight trials could be scored. The mean proportion of trials in which children opened the correct door in this subset of trials was $M = 0.37$, comparable to the mean proportion obtained across all trials ($M = 0.36$).

Point-of-gaze data from the eye tracker were used to determine if the child fixated on the barrier at least once during the hiding event (defined as the time between the onset of the ball's rolling and the opening of a door). Two scorers coded all the eye movement data with 98% inter-rater reliability. In case of disagreement, the judgment of a third scorer was used.

While all of the children looked at the barrier when it was placed on the ramp, they looked at it on only 20% of the trials during the rolling event. Given infrequent gaze at the barrier, stable conditional probabilities could not be determined for individual children. Across children, successful search was found in only 25% of the trials in which children looked at the barrier (Fig. 3). This performance was lower than the overall mean ($M = 0.36$), and does not exceed what would be predicted by chance. These data clearly show that correct search does not increase when children look at the barrier.

2.2. Children's tracking of the ball

Children's eye-movements were further scored as to whether children tracked the ball as it rolled between the doors. A trial was coded as *track correctly* (i.e., eye followed the ball while it rolled and then stopped at the door with the barrier), *track past* (i.e., eye continued tracking the ball in the imagined trajectory of the ball after the ball stopped), *stop tracking early* (i.e., eye stopped tracking the ball before it stopped rolling), or *no tracking* (i.e., any other looking pattern). This scoring scheme follows the one used in Butler et al. (2002). The inter-rater reliability between two scorers was 91% agreement, with the judgment of a third scorer being used in the case of disagreement.

The most frequent pattern was to track the ball correctly until it stopped at the barrier (47%) (Fig. 4a), followed by the pattern in which children tracked the ball past the door behind which it stopped (40%) (Fig. 4b). Children stopped tracking the ball early in only 4% of the trials, and showed no discernable tracking pattern in 9% of the trials.

To determine whether children's patterns of tracking the ball predict their search performance, two conditional probabilities were calculated for each child, one reflecting the probability that children opened the correct door given that they tracked the ball correctly, and the other reflecting the probability that children opened the correct door given that they tracked the ball incorrectly. We included only those children who tracked the ball correctly on at least three trials, and who showed other looking patterns on at least three trials ($n = 19$) in order to have stable within-subject

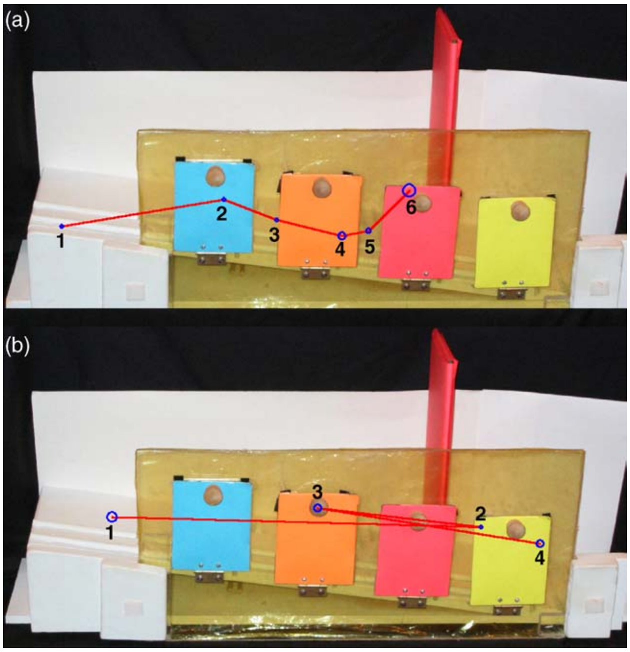

Fig. 4. Scanning trajectories and fixations: (a) when the child opened the correct door, and (b) when the child opened an incorrect door. Typically, during a correct trial, the child's point-of-gaze would follow the ball to the correct door. During a typical incorrect trial the child would not track the ball, and would typically open a door past where the ball came to a stop. Numbers indicate the fixation number and the diameter of the circle represents the length of the fixation. A small circle indicates the child looked for only a small amount of time, whereas a large circle indicates the child looked for a longer amount of time.

scores for this comparison. A repeated-measure t-test revealed a significant difference between these two probabilities ($t(18) = 4.39$, $p < 0.001$), with children being more likely to open the correct door when they tracked the ball correctly ($M = 0.49$, S.D. = 0.25) than when they showed other looking patterns ($M = 0.24$, S.D. = 0.22).

3. Discussion

The use of eye tracking in this search task revealed a clear difference in children's ability to use different cues. When children tracked the rolling ball correctly, they were about twice as likely to open the correct door as when they stopped tracking early, tracked past the ball's stopping location, or did not track the ball at all. In contrast, fixations of the barrier during a trial were infrequent, and when they did occur, performance was at chance. When 2-year-olds pay attention to dynamic cues directly related to the hidden location, performance improves. Moving objects are known to recruit visual attention from early infancy (White, Castle, & Held, 1964) and movement remains a powerful attention-getter throughout life. Tracking the ball in this task, however, does not insure children's correct choice of a door. About half of the time when they followed the ball, children ignored the direct information of the object's last disappearance. Butler et al. (2002) showed that 2.5-year-olds, in contrast to 2-year-olds, opened the correct door about 85% of trials when they had tracked correctly.

The eye movement data proved most valuable in laying to rest questions concerning how the spatial integration of barrier and door might be made easier for 2-year-olds. Our data show that children this age disregard the barrier as an informative factor in the search process. They usually do not look at it during the rolling event, and if they happen to, it does not remind them of its significance in stopping the ball. Thus, it is no surprise that matching barrier and door in color did not help performance at all. It is possible that children's eye movements may have been diverted from the wall because of the moving ball, which by nature of the movement was inherently more interesting than the stationary wall. On the other hand, when 2-year-olds viewed the rolling ball with no screen hiding its movement and it came to rest at the wall, performance was little improved (Mash, Keen, & Berthier, 2003). In that study the screen was lowered only after the ball stopped rolling, giving the children a clear view of the ball resting against the barrier. When the screen was lowered, the top part of the barrier was still visible above the screen. Even so, children opened the correct door only 37% of trials, compared to 36% in the current study.

The barrier is a more abstract cue, requiring not only spatial integration but also reasoning, compared to the direct spatiotemporal information of object movement and disappearance. This distinction between spatiotemporal information and contact-mechanical knowledge about the barrier has been described by Scholl and Leslie (1999), and tested in macaques (Hauser, 2001; Santos, 2004). Reasoning about the barrier's role was found to be absent in macaques, whereas they could use spatiotemporal information in search (Santos, 2004). By 3 years of age children readily use both types of cues, and even weigh them appropriately when they are in conflict (Haddad, Kloos, & Keen, 2004).

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References

Aslin, R., & McMurray, B. (2004). Automated corneal-reflection eye tracking in infancy: Methodological developments and applications to cognition. *Infancy*, *6*, 155–163.

Baker, R. K., Klitzing, P. A., & Keen, R. (2005). *Examining toddlers' difficulty in predicting the location of a ball in a search task*. Poster presented at the 2005 biennial meeting of the Society for Research in Child Development, Atlanta GA, April 2005.

Berthier, N. E., DeBlois, S., Poirier, C. R., Novak, M. A., & Clifton, R. K. (2000). Where's the ball? Two- and three-year-olds reason about unseen events. *Developmental Psychology*, *36*, 394–401.

Butler, S. C., Berthier, N. E., & Clifton, R. K. (2002). Two-year-olds' search strategies and visual tracking in a hidden displacement task. *Developmental Psychology*, *38*(4), 581–590.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development*, *65*(2), serial number 261.

DeLoache, J. S. (1986). Memory in very young children: Exploitation of cues to the location of a hidden object. *Cognitive Development*, *1*, 123–137.

Diamond, A. (1998). Understanding the A- not B-error: Working memory vs. reinforced response, or active trace vs. latent trace. *Developmental Science*, *1*, 185–196.

Haddad, J. M., Kloos, H., & Keen, R. (2004). *Cognitive strategies in a dynamic search task: effects of congruent and conflicting cues*. Poster presented at the 14th Biennial International Conference on Infant studies, Chicago IL, May 2004.

Hauser, M. D. (2001). Searching for food in the wild: A nonhuman primate's expectations about invisible displacement. *Developmental Science*, *4*, 84–93.

Hood, B. M., Carey, S., & Prasada, S. (2000). Predicting the outcomes of physical events: Two-year-olds fail to reveal knowledge of solidity and support. *Child Development*, *71*, 1540–1640.

Hood, B. M., Cole-Davies, V., & Dias, M. (2003). Looking & search measures of object knowledge in pre-school children. *Developmental Psychology*, *39*, 61–70.

Keen, R. (2003). Representation of objects and events: Why do infants look so smart and toddlers look so dumb? *Current Directions in Psychological Science*, *12*, 79–83.

Keen, R. (2005). Using perceptual representations to guide reaching and looking. In J. J. Rieser, J. L. Lockman, & C. A. Nelson (Eds.), *Action as an organizer of learning and development: Minnesota symposia on child psychology, vol. 33* (pp. 301–322). Mahwah, NJ: Lawrence Erlbaum Associates.

Kloos, H., & Keen, R. (2005). An exploration of toddler's problems in a search task. *Infancy*, *7*, 7–34.

Mash, C., Keen, R., & Berthier, N. E. (2003). Visual access and attention in two-year-olds' even reasoning and object search. *Infancy*, *4*, 371–388.

Santos, L. R. (2004). 'Core knowledges': a dissociation between spatiotemporal knowledge and contact-mechanics in a non-human primate? *Developmental Science*, *7*, 167–174.

Scholl, B. J., & Leslie, A. M. (1999). Explaining the infant's object concept: Beyond the perception/cognition dichotomy. In E. Lepore & Z. Pylyshyn (Eds.), *What is cognitive science?* (pp. 26–73). Oxford: Blackwell.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*(2), 605–632.

White, B., Castle, R., & Held, R. (1964). Observations on the development of visually-directed reaching. *Child Development*, *35*, 349–364.