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PAPER

# Object boundaries influence toddlers′ performance in a search task

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## Abstract

*Previous research has shown that young children have difficulty searching for a hidden object whose location depends on the position of a partly visible physical barrier. Across four experiments, we tested whether children's search errors are affected by two variables that influence adults' object-directed attention: object boundaries and proximity relations. Toddlers searched for a car that rolled down a ramp behind an occluding panel and stopped on contact with a barrier. The car's location on each trial depended on the placement of the barrier behind one of two doors in the panel. In Experiment 1, when a part of the car (a pompom on an antenna) was visible at the same distance from the object as the barrier wall in past research, search performance was above chance but below ceiling. In Experiments 2 and 3, when the visible part was close to the hidden body of the car and could be seen through one of two windows in the doors of the occluding panel, performance was near ceiling. In Experiment 4, when only the barrier was visible through one of the same windows, performance was at chance. Toddlers' search for a hidden object therefore is affected by the proximity of a visible part of the object, though not by the proximity of a separate visible landmark. These findings suggest a parallel between the object representations of young children and those of adults, whose attention is directed to objects and spreads in a gradient-like fashion within an object.*

## Introduction

Young children perform surprisingly poorly on manual object search tasks that are modeled after looking-time tests of physical knowledge in infancy (e.g. Berthier, DeBlois, Poirier, Novak & Clifton, 2000; Hood, Carey & Prasada, 2000). Such findings have perplexed researchers and inspired a series of studies seeking to explain young toddlers' difficulty (Butler, Berthier & Clifton, 2002; Hood, Cole-Davies & Dias, 2003; Mash, Keen & Berthier, 2003; Mash, Novak, Berthier & Keen, in press). Many papers have rooted toddlers' search errors in qualitative differences between the cognitive capacities of young children and adults (e.g. Berthier *et al*., 2000; Hood, 2004). Here we offer an alternative account of children's search patterns that draws a parallel between children's search for hidden objects and adults' performance in tasks of object-directed attention. Across four experiments, we manipulated object boundaries and proximity relations to ask whether factors that influence adults' attentive tracking of objects account for toddlers' search performance.

Our task was adapted from Berthier *et al*. (2000) in which toddlers searched for a ball that had been rolled down a ramp, behind an occluding panel with four doors. The location of the hidden ball on each trial depended on the position of a moveable wall whose top was visible above the occluding screen. Children under the age of 3 performed at chance in choosing the correct door on this task, despite an elaborate training and familiarization procedure. In experiments using different materials and only two choices (Hood *et al*., 2000), 2-year-old children also performed poorly when searching for a hidden object whose location depended on the position of a solid barrier. When a ball was dropped behind an occluding panel that partly hid a horizontal shelf, for example, most children searched incorrectly below the shelf.

Both the Berthier *et al*. (2000) and the Hood *et al*. (2000) tasks were modeled after preferential looking-time experiments probing young infants' knowledge of object solidity (two objects cannot occupy the same place at once) and continuity (objects move only on connected paths) (Spelke, Breinlinger, Macomber & Jacobson,

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1992). For example, in Experiment 3 of Spelke *et al.* (1992), infants were familiarized with a ball rolling from left to right across a stage, behind an occluding panel. At the end of each familiarization trial, the occluding panel was lifted to reveal the ball resting against a wall whose top had been visible above the occluding panel. In the test phase, a second barrier wall was placed to the left of the original wall (perpendicular to the occluding panel) and infants again were shown a ball rolling across the stage, behind the occluding panel. On alternating trials, the panel was lowered to reveal the ball resting either to left of the barrier wall (an event novel in appearance, but consistent with laws of continuity and solidity) or to the left of the original wall (an event familiar in appearance, but inconsistent with those laws). Infants looked longer at trials of the latter type, whereas infants in a control condition who were presented with the same outcomes after a set of physically consistent events, did not. The findings provided evidence that infants as young as 2.5 months of age represent hidden objects and extrapolate object motion in accord with physical laws.

Young toddlers' search failures therefore stand in stark contrast to the success of infants in preferential looking experiments. Two further findings with toddlers provide evidence that this contrast does not stem from any decline or deficiency in children's understanding of object solidity and continuity. First, toddlers tested on a looking-time task using the apparatus designed by Berthier *et al.* (2000) looked longer in the test trials at outcomes that implied the object had violated constraints on object motion after it rolled behind the occluding panel (Hood *et al.*, 2003; Mash *et al.*, in press), as did the infants tested by Spelke *et al.* (1992). Specifically, toddlers looked longer when a ball appeared to have rolled through the barrier wall or jumped from one location to another on a discontinuous path. Second, toddlers who viewed the entire motion event in the reaching study still performed poorly (Mash *et al.*, 2003). In Mash *et al.* (2003), toddlers saw a ball roll down the ramp and stop by the barrier wall before the experimenter lowered the occluding panel with four doors. Subsequent search did not depend on knowledge of continuity and solidity, as the ball's final location had been observed, yet 2-year-old children still failed to find the ball. Limits on children's physical knowledge evidently cannot account for the limits on their search performance.

Researchers have proposed a variety of explanations to account for the poor performance of 2-year-old children on these manual reaching tasks. For example, perhaps infants and young toddlers are unable to recruit their knowledge of physical constraints on object motion in the service of object search, because their representations are not strong enough to support manual performance or predictions of a moving object's future position (Berthier *et al.*, 2000; Hood *et al.*, 2000; Hood *et al.*, 2003; Keen, 2003; Kloos & Keen, 2005). Alternatively, perhaps toddlers are unable to demonstrate their knowledge of the location of the ball due to general difficulties with spatial integration (Keen, 2003, 2005; Mash *et al.*, 2003). According to the spatial integration hypothesis, toddlers' poor performance stems from an inability to integrate their perception of the location of the barrier wall with the position of the door, a requirement for executing a correct search. In order to spatially integrate the wall and door, however, children must attend to the position of the barrier wall. A study in which participants wore an eye-tracker while being tested on the original Berthier *et al.* (2000) apparatus found that toddlers spent very little time looking at the barrier wall once the ball had been released to roll down the ramp (Haddad, Kloos & Keen, 2004). It seems that young toddlers do not even attempt to use the location of the barrier wall to find the ball.

Since the task of using the barrier wall to locate and open the correct door is trivial for adults (and children over the age of 3), many researchers have appealed to qualitative differences between the capacities of toddlers and adults to explain toddlers' poor performance. Research comparing the signatures of object representation in infants and adults has suggested, however, that attentional mechanisms might be continuous across development (Carey & Xu, 2001; Feigenson, Dehaene & Spelke, 2004; Scholl & Leslie, 1999). We hypothesized that common mechanisms could underlie the object-directed search of young toddlers and adults, despite dramatic developmental changes in search performance.

In adults, attention is directed to whole objects (Baylis & Driver, 1993; Duncan, 1984), spreads continuously within an object (e.g. Egly, Driver & Rafal, 1994; Scholl, Pylyshyn & Feldman, 2001) and stays focused on the object when it moves in and out of view on paths that are continuous (Scholl & Pylyshyn, 1999). Adults' object tracking fails when an object moves discontinuously (Scholl & Pylyshyn, 1999) or noncohesively (vanMarle & Scholl, 2003), and it fails to take account of the positions of other objects in the scene (Scholl & Pylyshyn, 1999). These findings suggest parallels with the performance both of infants tested in preferential looking experiments and of young children tested in object search tasks (Carey & Xu, 2001; Scholl, 2001).

Do young children's errors in the search tasks of Berthier *et al.* (2000) and Hood *et al.* (2000) reflect constraints on mechanisms of object-directed attention? If such constraints apply to children, then toddlers may search more effectively if they can see part of the object to be tracked, because their attention should spread from the visible part to the hidden body of the object. Experiment 1 tested this prediction.

## Experiment 1

Experiment 1 investigated children's search for an occluded rolling object (a car) with a visible part (a pompom). The pompom was separated from the car's body by the same distance as the barrier wall in previous research. However, it moved with the car, was attached to it by an antenna and remained visible throughout the event.

### *Method*

#### Participants

Sixteen children participated in the experiment (seven females, nine males; mean age = 25 months, 1 day; range = 24 months, 12 days–25 months, 18 days). Two additional children participated, but were not included in the final sample because they did not complete the minimum number of test trials. All parents and children were recruited from the Greater Boston area.

#### Materials

Figure 1 depicts the materials used in this experiment and all those that follow. The task apparatus was a wooden ramp with a moveable wall and a detachable occluding panel that contained two doors. A car could be rolled down the ramp to stop behind one of the two doors, depending on the position of a wall.

The ramp (73 cm long, 16 cm tall and 18 cm deep) was painted white and sloped downward from left to right. Two parallel, white wooden dowels placed 6 cm apart along the ramp's surface served as a track for the car, lined with white felt to minimize its rolling sound. Two white metal clips attached to the front of the ramp held the occluding panel.

The white, wooden 28 × 57 cm occluding panel contained two rectangular openings 16 cm apart, covered by 15 × 11.5 cm grey wooden doors that were hinged to the panel at their bases. The left door was positioned near the center of the apparatus. Weak magnets held each door closed as the experimenter manipulated the apparatus. A wooden knob placed near the top of each door allowed easy opening by the child.

Two removable bright green walls (one for each door location) were used to stop the car on the track. Both walls were 18 cm deep, 2 cm thick and 8.5 cm taller than the occluding panel. The base of the ramp contained two slots, one to hold each wall in its place, corresponding to the rightmost part of the door opening and perpendicular to the position of the occluding panel. A piece of white foamcore (73 cm long and 51 cm tall) was tacked to the back of the ramp to create a high-contrast background for the appearance of the wall and car.

A small (6 cm long, 2.5 cm wide and 2 cm tall) purple metallic toy car was rolled down the ramp on each trial. A bright pink fuzzy pompom (1.5 cm diameter) was attached to the car by a 28-cm tall silver wire antenna. When the car came to rest to the left of a wall, the pompom stood approximately 16 cm above the top of the appropriate door and 10 or 6 cm above the occluding panel. A video camera situated behind the child recorded the session for use in offline coding.

#### Procedure

During the experiment, the child sat in a chair facing the ramp apparatus on a table and the experimenter stood on the other side of the table behind the apparatus and facing the child. Before introducing the child to the ramp, the experimenter showed the toy car to the child, emphasizing the special antenna and pompom.

The experiment began with a familiarization phase that introduced the child to the ramp apparatus. On the first two familiarization trials, the experimenter placed one wall in the ramp, called the child's attention to the car at the top of the ramp, pointed out the pompom on the car, and then released the car, which rolled down the ramp in full view and stopped at the wall, once in each location. The experimenter remarked that the car had stopped at the wall, pushed the apparatus toward the child, and asked the child to retrieve the car. For the next two trials, the experimenter placed one wall in the ramp, put the occluding panel down in front of the ramp, opened both doors, called the child's attention to the car at the top of the ramp, pointed out the pompom, and then released the car. After the car stopped at the wall, the experimenter closed both of the doors simultaneously, pushed the apparatus forward, and asked the child to retrieve the car. If the child opened the correct door, the experimenter cheered, allowed the child to retrieve the car, and administered the trial at the other wall. If the child opened the incorrect door or opened both of the doors simultaneously, the experimenter opened the door at the correct location, pointed out the pompom visible above the occluding panel, and then repeated the trial at that same wall before moving on to the trial(s) at the other wall. Throughout familiarization and test, only one wall was in the ramp on any given trial. Additionally,

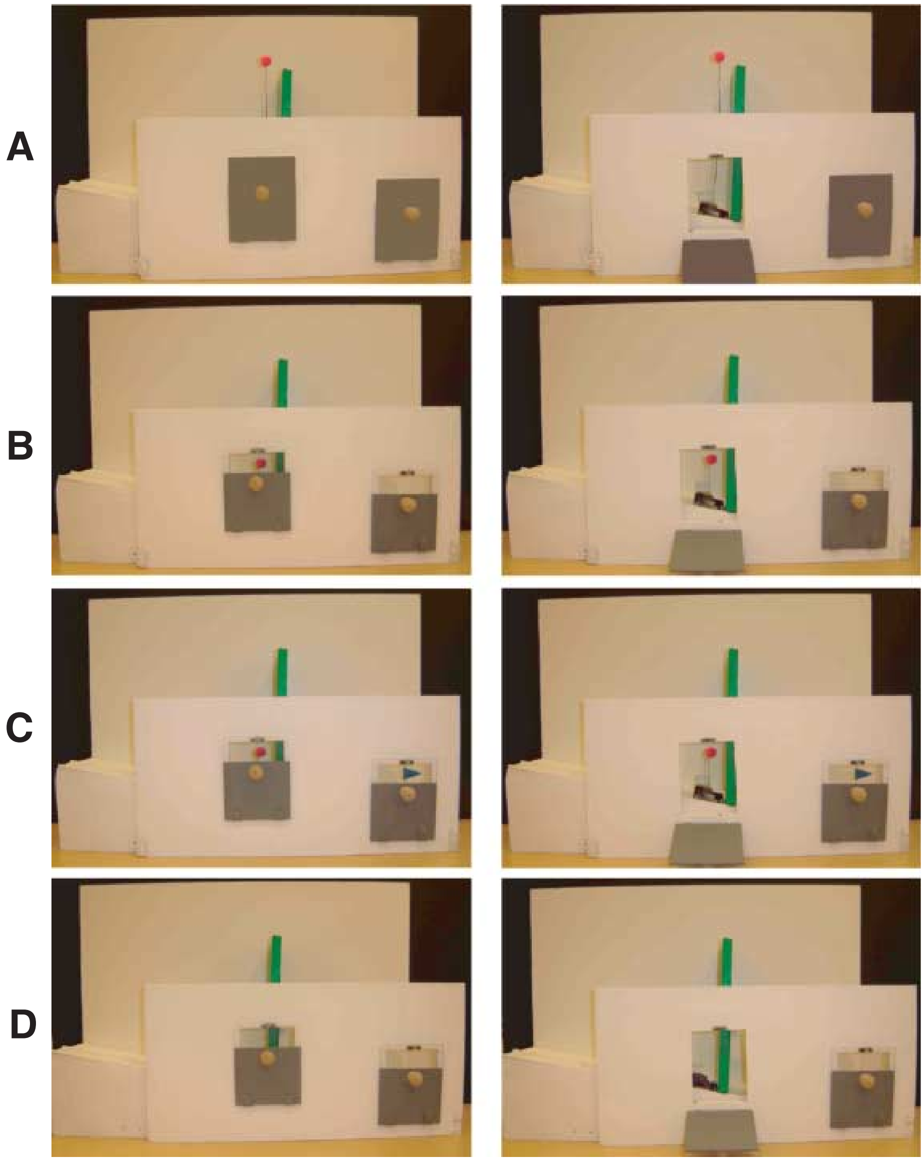

**Figure 1** *(A) The materials in Experiment 1. (B) The materials in Experiment 2. (C) The materials in Experiment 3. (D) The materials in Experiment 4.*

the apparatus always remained far enough away from the child to prevent him/her from being able to see the car when it went behind the occluding panel.

After familiarization, children completed between 10 and 12 test trials (the experiment was terminated after 10 trials if the child indicated that s/he did not want to do any additional trials). On each test trial, the experimenter placed a wall in the ramp, lowered the occluding panel, called the child's attention to the car at the top of the ramp, pointed out the pompom, and then released the car. After the car came to rest at the wall, the experimenter pushed the apparatus toward the child and asked the child to get the car. On trials where the child opened the correct door, the experimenter cheered, allowed the child to obtain the car, and moved on to the next test trial. On trials where the child opened the incorrect door, the experimenter showed the child the car behind the correct door and directed the child's attention to the pompom above the panel.

## Design

During familiarization, the wall was placed behind the left (L) or right (R) door in one of two orders: LRRL or

RLLR. Additionally, there were two possible pseudo-random orders for the test trials: LRLLRLRRLRLR or RLRRLRLLRLRL. The experiment was counter-balanced such that half of subjects received the first familiarization phase order, while the remainder received the second order. Of the subjects who received the first familiarization order, half received the first test trial order, while the remainder received the second test trial order. Likewise, of the subjects who received the second familiarization order, half received the first test trial order, while the rest received the second test trial order. This resulted in a fully counterbalanced design.

### Scoring and analysis

The experiment was coded online by an observer sitting behind the child. A secondary coder scored four randomly selected sessions offline from videotapes for reliability. Coders counted only the child's first choice (whichever door the child pulled open first); trials were scored as either correct or incorrect. Reliability for Experiment 1 was 100%. If the child opened both doors at once, the trial was excluded from analysis. In Experiment 1, two trials were excluded for this reason.

The percentage of correct searches on the test trials was calculated for each child. Because these percentages were normally distributed, performance was compared to chance by a single-sample *t*-test. In order to assess position biases and improvement over the course of the session, the percentage of correct searches at each door and the percentage of correct searches for the first five trials vs. the last five trials in a session were calculated for each child. Since these variables were not normally distributed, Wilcoxon signed-ranks tests were used for these comparisons.

### *Results*

Most children completed 12 trials; two children contributed only 10 trials. Search performance on test trials was above chance ($M$ = 62%, chance = 50%, $t(15) = 2.49$, $p < .05$; see Figure 2, left). Performance was better on trials where the car was behind the left door ($M$ = 82%) than on trials where the car was behind the right door ($M$ = 41%), suggesting that children had a bias for the door located at the center of the display ($z = 3.07$, $p < .01$, Wilcoxon signed-ranks test). Toddlers performed similarly on the early ($M$ = 64%) and later ($M$ = 61%) trials in a session (Wilcoxon $z = .55$, *ns*).

### *Discussion*

In contrast to earlier research with fully hidden objects, toddlers' performance was above chance when they could see part of the object for which they were searching. Nevertheless, children still made search errors on more than one-third of the trials. Children showed a bias toward the centrally located door on our 2-door apparatus, in accordance with findings from previous research reporting a bias for the middle doors in a 4-door apparatus (e.g. Berthier *et al.*, 2000). These findings reveal the magnitude of toddlers' difficulty with directing correct searches in this task.

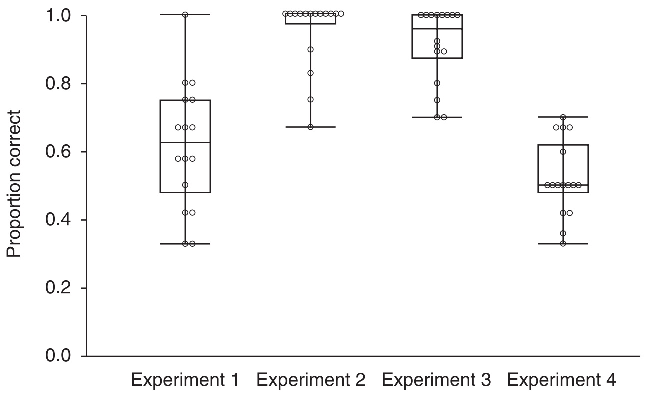


**Figure 2** *Proportion of correct searches by children in Experiments 1–4. Each circle represents one child's performance. Bars and boxes indicate the median and interquartile range.*

We hypothesized that the distance from the pompom to the door and car might be the cause of toddlers' mediocre performance, for one of two reasons. First, perhaps toddlers realized that the pompom indicated the location of the rest of the car, but had trouble lining up the pompom with the correct door. Alternatively, children's errors may have stemmed from an incomplete spread of attention from the visible pompom to the hidden car. Studies of object-direction attention with adults indicate that attention spreads in a gradient-like fashion within an object. For example, Egly *et al.* (1994) demonstrated the automatic spread of attention within an object using a cueing paradigm. In one condition, subjects were presented with a pair of rectangles that were oriented vertically and their task was to detect a target (a grey square) at one of the four ends of the rectangles. Before the target appeared, subjects were cued (by a brightness change) to one of the four locations. On trials where the cue was invalid (i.e. did not appear at the same location as the target), adults were faster to detect the target when it appeared within the object (but at the uncued end) than when it appeared in the other rectangle at an equal distance from the cue, demonstrating a 'same-object advantage'. Subjects also showed an advantage for the near location within the cued object; that is, subjects were faster to detect the target when it appeared in the cued location than when it appeared at the other end of the same rectangle. Perhaps toddlers directed their attention to the pompom, but due to gradient effects, attention did not spread fully to the car.

Experiment 2 therefore investigated whether increasing the proximity of the visible part (pompom) to the hidden object (car) would boost children's search performance. The car's antenna was shortened to a quarter of its previous length, and windows were created in both doors so that children could see the pompom through the correct door.

## Experiment 2

### Method

The method was the same as Experiment 1, except as follows. The participants were eight male and eight female children with a mean age of 24 months, 25 days (range = 24 months, 3 days–25 months, 19 days). One additional child did not complete the minimum number of test trials required to be included in the final sample.

The task apparatus was exactly the same as in Experiment 1 except that the two doors in the occluding panel were made of transparent plexiglas rather than wood. The lower portion (about two-thirds) of each door was painted grey to make it opaque, while the top part of each door was left transparent. When the doors were closed, children could see the car's antenna and pompom through the window, but they were seated at a height and distance from the ramp that made it impossible for them to see the car's body. The car was the same as the one used in Experiment 1 except that the antenna was shortened from 28 cm to 7.5 cm so that the pompom was visible through the window. The only additional change to the method was that half of subjects were tested with the tall green walls described in Experiment 1, while the other half of subjects were tested with a very short green wall that was 18 cm deep, 2 cm thick and 4 cm tall. Thus, the short wall was not visible (either through a door or above the panel) once the occluding panel was in place. As in Experiment 1, reliability between coders was 100%. Because test performance was not normally distributed, it was analyzed by non-parametric statistics.

### Results

The majority of children completed 12 trials; five children contributed only 10 trials to the analyses. Search performance in Experiment 2 was excellent ($M = 95\%$). Indeed, 14 of 16 infants performed correctly on at least 9 of 10 or 10 of 12 trials, yielding above-chance performance for each of those children individually (binomial $p < .05$, 1-tailed). There was no difference between the performance of children tested with the tall (visible) walls and children tested with the short (not visible) wall ($M = 91\%$ vs. $M = 99\%$, respectively). Toddlers performed marginally better on trials where the car was behind the left ($M = 98\%$) than the right ($M = 91\%$) door, but this trend was not statistically significant ($z = 1.84$, $p < .10$, Wilcoxon signed-ranks test). Toddlers showed no improvement from the early trials ($M = 94\%$) to the later trials ($M = 94\%$).

Comparing the test trial performance of Experiment 2 to that of Experiment 1, the distributions of the two experiments differed significantly ($z = 4.28$, $p < .001$, Mann-Whitney test). Figure 2 illustrates the difference between the distributions of the first and second experiments. Reliably more children performed above chance in Experiment 2 (14 children) than in Experiment 1 (1 child; $X^2(1) = 21.21$, $p < .001$).

### Discussion

When children were able to see part of a hidden object through a window that was close to that object, they succeeded robustly in finding that object. Children's superior performance in this condition, relative to that in Experiment 1, suggests that young children's search is affected by the proximity of a visible part to a hidden object. Nevertheless, this conclusion could be questioned for two reasons. First, children in Experiment 2 might have chosen the correct door simply because it was the only one with something visible behind it, rather than because they knew the pompom marked the location of the car. Second, in Experiment 2 the car was fully occluded from the time it moved behind the panel to the time it appeared at one of the doors, whereas in Experiment 1, some part of the car was always in view. We had originally thought this factor would make Experiment 2 more demanding than Experiment 1. However, if toddlers' attention is drawn to movement on the apparatus, then perhaps toddlers were more successful in Experiment 2 because the movement appeared close to (i.e. immediately behind) the correct door.

Experiment 3 was undertaken to control for these possibilities and probe further the differential success of children in the first two experiments. Experiment 3 used the procedure and materials from Experiment 2, but with an object (a pompom or flag) visible in each window. One object was part of the car; the other object (the 'distractor') was simply placed in the window of the incorrect door. In order to investigate the possibility that toddlers simply reached for the location on the apparatus where the most recent movement had occurred, we alternated between two kinds of trials in Experiment 3: On 'distractor-first' trials, the distractor was put into place first and then the car was rolled; thus, the final movement on the apparatus occurred behind the correct door (when the car moved into view). On 'roll-first' trials, the car was rolled first and then the distractor was put into place; thus, the final movement on the apparatus occurred at the incorrect door. A comparison of these two types of trials should illuminate the role of movement in guiding toddlers' search.

## Experiment 3

### *Method*

The method was the same as Experiment 2 except as follows. Nine female and seven male children participated (mean age = 24 months, 30 days; range = 24 months, 13 days–25 months, 11 days). Two trials were excluded from analyses because children opened both doors at once. Identical distractor objects on wire antennae were attached to the back of the occluding panel, one above each door. The objects could be rotated into place by the experimenter; otherwise, they remained hidden from the child's view. For half of subjects the distractor was a blue flag on wire antenna, while the visible part on the car was a pink pompom on a wire antenna; for the remaining subjects the distractor was a pink pompom on a wire antenna, while the visible part on the car was a blue flag on a wire antenna. For every child, trials where the distractor was put into place before the car was rolled ('distractor-first' trials) were alternated with trials where the distractor was put into place after the car came to rest at the wall ('roll-first' trials). Half of subjects started with a distractor-first trial, while the remainder started with a roll-first trial.

On distractor-first trials, the experimenter placed a wall in the ramp, lowered the occluding panel, put the distractor into place, called the child's attention to the car at the top of the ramp, pointed out the pompom or flag on the car, and then released the car. After the car came to rest at the wall, the experimenter pushed the apparatus toward the child and asked the child to get the car. On roll-first trials, the experimenter placed a wall in the ramp, lowered the occluding panel, called the child's attention to the car at the top of the ramp, pointed out the pompom or flag on the car, and then released the car. After the car came to rest at the wall, the experimenter put the distractor into place and then pushed the apparatus toward the child, and asked him/her to get the car. Inter-rater reliability between coders was 100% in Experiment 3. Performance was not normally distributed and was analyzed by nonparametric statistics.

### *Results*

Eight children completed 12 trials, one child contributed 11 trials, and seven children contributed 10 trials. Average search performance in Experiment 3 was near ceiling ($M$ = 91%) and 12 (out of 16) individuals exceeded chance-level performance (9 of 10, 9 of 11, or 10 of 12 correct trials). Performance in Experiment 3 did not differ from that of Experiment 2 ($z$ = 1.19, *ns*, Mann-Whitney test); the number of children performing above chance also was similar in the two experiments ($X^2(1)$ = .82, *ns*). Note the similarity of distributions for Experiments 2 and 3 in Figure 2.

As in Experiment 2, there was no difference between the performance of children tested with the tall (visible) walls and children tested with the short (not visible) wall ($M$ = 92% vs. $M$ = 91%, respectively). Toddlers performed slightly better on trials where the car was behind the center ($M$ = 97%) rather than the right ($M$ = 86%) door, but this trend was not significant (Wilcoxon $z$ = 1.76, $p < .10$). Toddlers showed no improvement from the early ($M$ = 89%) to the later ($M$ = 93%) test trials ($z$ = .63, *ns*), and they performed equally well on 'distractor-first' ($M$ = 92%) and 'roll-first' ($M$ = 90%) trials ($z$ = .43, *ns*).

### *Discussion*

Children robustly succeeded in locating the hidden object in this experiment. Because a visible object appeared at each door, children's correct search cannot be attributed to a direct effect of the pompom/flag on the attractiveness of the door. Instead, children used the appropriate cue to guide their search for the hidden car. Additionally, children performed equally well on 'distractor-first' and 'roll-first' trials, suggesting that even when the most recent movement on the apparatus appeared in the incorrect window, children were able to direct a correct reach to the car. Together, Experiments 2 and 3 provide evidence that young children's search is affected by the proximity of a visible part to a hidden object.

The results from Experiments 1–3, together with findings from previous studies, are open to two interpretations. First, proximity alone may be the critical factor in determining toddlers' success when searching for a hidden object. Whenever a cue to the location of the hidden object is relatively far from the hidden object itself (i.e. the tall antenna in Experiment 1 or the wall in previous studies), toddlers may perform poorly. Toddlers may perform well, in contrast, whenever the cue to the location of the hidden object is relatively close to the object itself (i.e. the short antenna in Experiments 2 and 3), perhaps because it is easier for toddlers to spatially integrate the cue with the correct door.

Alternatively, cue proximity may be a critical factor only when the cue is part of the hidden object. For infants as for adults (Egly *et al*., 1994), object boundaries may modulate the proximity effect. To decide between these alternatives, children in Experiment 4 were presented with a cue to the object's location that was visible through the same windows (and therefore at the same distance) as in Experiments 2 and 3, but was not attached to the car: the wall itself.

## Experiment 4

### Method

Sixteen children participated in the experiment (nine females; seven males; mean age = 24 months, 30 days; range = 24 months, 3 days–25 months, 21 days). Two additional children participated, but did not complete enough trials to be included in the final sample. Three trials were excluded from analyses because children climbed onto the table and thus could see the track through the windows in the doors. Inter-rater reliability was 100%.

Experiment 4 used the same task apparatus as Experiment 2, with three modifications: Only the tall walls with visible tops were used, the car was presented without the antenna and pompom, and the occluding panel was shifted slightly to the right so that when in place, the wall appeared near the middle of the window of the appropriate door. Before the car was rolled, the experimenter pointed out the location of the wall, just as she had pointed out the visible part of the car at the start of each trial in Experiments 1–3. Because the wall occupied approximately the same position relative to the door as the pompom in Experiment 2, a comparison of performance in Experiment 4 to that of Experiment 2 should reveal whether a proximal cue enhances search if the cue is not part of the hidden object.

### Results

Ten children completed 12 trials, one child contributed 11 trials, and five children contributed 10 trials. Search performance was at chance ($M$ = 52%, $t(15) = .74$, *ns*). Toddlers' performance on trials where the car was behind the left door ($M$ = 65%) was not significantly different from their performance on trials where the car was behind the right door ($M$ = 39%) (Wilcoxon $z = 1.57$, *ns*). Toddlers showed no improvement over the course of the session; in fact, their performance was marginally worse at the end ($M$ = 48%) than at the start ($M$ = 58%) of the session, but this trend was not significant (Wilcoxon $z = 1.89$, $p < .10$). Comparing Experiment 4 to Experiment 2 revealed a significant difference in children's performance (Mann-Whitney: $z = 4.89$, $p < .001$) and in the number of children performing above chance ($X^2(1) = 24.89$, $p < .001$). Note the difference between the distributions for Experiments 2 and 4 in Figure 2.

### Discussion

In contrast to Experiments 2 and 3, children failed to locate the object in Experiment 4, despite the presence of a visible cue in close proximity to the object's location. The critical difference between Experiments 2 and 4 concerned the nature of this cue: in Experiment 2, it was part of the object; in Experiment 4, it was part of the apparatus that stopped the movement of the object. When a visible cue is located near the hidden body of an object, its effectiveness therefore depends on its connection to the object. Although cue proximity enhances young children's search performance when the cue is part of the hidden object (Experiment 1 vs. Experiment 2), it fails to enhance young children's search performance when the cue is part of a different object (Experiment 2 vs. Experiment 4).

The poor performance of children in Experiment 4 casts doubt on the hypothesis that children simply have difficulty integrating a relevant cue with the correct door, due to the distance between the two (e.g. Keen, 2003, 2005; Mash *et al*., 2003). In Experiment 4, the barrier wall was clearly visible through the window of the correct door so that children did not have to integrate the components over a great distance. Moreover, the wall in Experiment 4 was visible at the same distance as the pompom in Experiments 2 and 3, where children's search performance was excellent.

## General discussion

Four experiments provide evidence that toddlers' manual search for a hidden object is affected by object boundaries and proximity relations. When toddlers could see part of the hidden car (i.e. the pompom) above the occluding panel in Experiment 1, they performed above chance. When that same object part was moved closer to the hidden body of the car in Experiments 2 and 3, toddlers' performance was near ceiling (and better than in Experiment 1), demonstrating that proximity affects search performance. Finally, when a cue that was not a part of the car was available for viewing at the same distance as the pompom/flag in Experiments 2 and 3, toddlers performed at chance, showing that object boundaries modulate the proximity effect observed in the preceding experiments.

The present results are consistent with the thesis that young children's object search is guided by attentional mechanisms that are common to children and adults. Experiments with adults reveal evidence for both object-based and location-based attention (Downing & Pinker, 1985; Posner, Snyder & Davidson, 1980; Scholl, 2001), depending on the paradigm and stimuli used (e.g. Vecera & Farah, 1994). In some experimental paradigms, results are consistent with the interpretation that both systems are present and interacting (Egly *et al.*, 1994; Soto & Blanco, 2004). The findings of the present experiments suggest that in young children, too, attention can be directed to an object and spreads from proximal to distal locations within the object.

At first glance, it is odd to link the performance exhibited by 2-year-old children on object search tasks and that of adults. For adults (and for children over the age of 3), the task of using the barrier wall to locate and open the correct door in the Berthier *et al.* (2000) apparatus is trivial. Experiments on adults suggest, however, that even adults' attention is surprisingly impervious to the position and behavior of objects that are not being tracked in a display. For example, Scholl and Pylyshyn (1999) asked adults to track multiple objects as they moved about a screen. In one experiment, object-tracking performance was examined under conditions involving a virtual (invisible) occluder that was either stable or unstable. In the latter condition, the occlusion events varied for each item in the display so that there was no globally consistent arrangement of occluding objects. Surprisingly, adults tracked the objects with equal success in the two conditions. When adults or children track a moving, occluded object, they appear to be oblivious to the positions of stationary objects that occlude or obstruct it.

The present findings accord with those from other laboratories, using other search tasks with infants and young children. In many situations, babies and toddlers perform better on object search tasks when a visual cue to the location of the hidden object is part of, rather than just adjacent to, the hiding place (Bushnell, McKenzie, Lawrence & Connell, 1995; DeLoache, 1986; Diamond, Churchland, Cruess & Kirkham, 1999; Diamond, Lee & Hayden, 2003). Limits on object-directed attention may account for all these findings.

If limits on the mechanisms of object-directed attention account for young children's search failures in the present tasks, what accounts for older children's success on these tasks? Our findings are consistent with two families of accounts. First, mechanisms of attentive object tracking may undergo quantitative changes in early childhood. With development, children may become able to keep track of a larger number of objects, over greater time delays, distances, distractions and memory loads (Ross-Sheehy, Oakes & Luck, 2003; Diamond, 1985), and this may influence their performance on object search tasks. For example, older children may be better able to divide their attention between a moving object and other visible objects in a display. Younger children may fail to take account of a stationary barrier as they track an object that moves toward it, because moving targets capture young toddlers' attention too strongly. To test the role of attentional capture of moving vs. stationary objects in the ramp task, one might alter the method of Experiment 4 so that the barrier wall slides into its final position at the same time as the car. Such a modification might improve young toddlers' search performance if attentional capture of moving objects contributed to the successes observed in Experiments 1–3.[1]

According to a second family of explanations, older children may circumvent the limits on object-directed attention by drawing on long-term memory representations of the position of the hidden object. When the barrier is placed on the ramp at the start of the trial, for example, older children may encode its position verbally (e.g. 'the wall is at the center of the ramp') and draw on this verbal code in the time of search. Alternatively, children may form a long-term visual representation of the array, and draw on this representation at the time of search. In either case, children could deduce the final position of the object without tracking its motion behind the screen, bypassing limits on object-directed attention.

These two accounts are not mutually exclusive, as developmental improvements in object search may stem from improvements in multiple memory mechanisms. Fortunately, each of the candidate attentional and memory systems has received intensive study in human adults, and that study has revealed a set of distinctive signature limits on the operation of each system. Experiments like the present ones may shed light on the changing capacities of young children by testing for these limits in children's search performance.

However these questions are resolved, our studies suggest a different perspective on children's search errors. In studies of adults, discussion often focuses on the adaptiveness of mature mechanisms of object-directed

[1] We thank an anonymous reviewer for suggesting this test.

attention (e.g. Scholl, 2001), which are sensitive to the most reliable constraints on objects' behavior. Objects are highly likely to maintain their cohesion and continuity as they move – they rarely disperse, coalesce or jump discontinuously from one place and time to another – but they are less likely to maintain constant positions over time, since many events can cause an object to move from one place to another. In studies of toddlers, in contrast, discussion often focuses on the maladaptiveness of children's object representations and object-directed actions. For example, toddlers' failure to take account of the position of a stationary object has been attributed to a lack of a capacity to represent hidden objects, a lack of sensitivity to basic constraints on object motion, inadequacies of attention and memory, or a disconnect between knowledge and action. Our findings suggest, however, that young children's search for hidden objects is guided by the same, highly reliable information that guides the attentive tracking of adults. The seemingly 'dumb' errors of young children may reveal the exquisitely adaptive character of core mechanisms for representing objects.

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