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Infants' tracking of objects and collections

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Abstract

Recent research suggests that infants' understanding of the physical world is more complex and adult-like than previously believed. One of the most impressive discoveries has been infants' ability to reason about medium-sized, material objects. They are able to individuate objects in a scene, and to enumerate and reason about them. This article reports a series of experiments investigating 8-month-old infants' ability to reason about *collections* of objects. Experiment 1 shows a sharp contrast between infants' understanding of single objects versus collections. While infants detected the discontinuous ('Magical') disappearance of a single object, they did not detect the Magical Disappearance of a non-cohesive pile of objects. Experiments 2–4 found that infants' difficulty remained even when the distinct identity of each object in the collection was emphasized, but could be overcome if infants (a) first saw the individual objects clearly separated from each other prior to their being placed together in a pile, or (b) had prior experience with the objects making up the collection. Our findings suggest that infants' expectations about object behavior are highly specific regarding the entities they are applied to. They do not automatically apply to any and all portions of matter within the visual field. Both the behavior of an entity, and infants' prior experience play roles in determining whether infants will treat that entity as an object. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Earlier in this century, it was believed that our knowledge of physical objects

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was constructed entirely as a result of our experience with the physical world; the very concept of a material object as an entity with an independent, enduring existence was seen as a developmental achievement laboriously attained over the first two or so years of life (Piaget, 1954). But recent studies (e.g. Baillargeon, 1986, 1995; Spelke, 1988; Spelke, Philips & Woodward, 1995) suggest that infants' understanding of objects may be considerably richer than this early picture suggested, and that some notion of what it is to be an object, together with some understanding of object behavior, may constitute a core domain of unlearned human knowledge.

One important property of physical objects is that they exist continuously over time and move on spatially continuous paths. Studies using habituation and preferential-looking methods suggest that infants expect the continued existence of objects that have been occluded from view (e.g. Baillargeon, 1986; Baillargeon, Spelke & Wasserman, 1985; Wynn & Chiang, 1998; Xu & Carey, 1996). For example, if infants view an object and then see it being occluded by a screen, they will look longer if the screen moves away to reveal nothing behind it than if it moves to reveal the object (e.g. Wynn & Chiang, 1998; Xu & Carey, 1996). One explanation for such findings is that infants possess a domain-specific system of knowledge of physical objects (e.g. Spelke, Breinlinger, Macomber & Jacobson, 1992), consisting of a set of principles that constrain the behavior of inanimate material objects. These include the principle of *cohesion* (a moving object maintains its connectedness and boundaries), the principle of *continuity* (objects exist enduringly and move only on connected paths through space and time), and the principle of *solidity* (objects move only on unblocked paths such that two objects never occupy the same place at the same time) (Spelke, 1988, 1990; Spelke et al., 1992). These principles are considered to serve two main functions for the infant. First, they capture the essence of what it is to be an object, providing criteria for object-hood that enable infants to pick out discrete objects in their environment. Second, these principles enable infants to predict and reason about the future behavior of an object, comprising, as it were, 'rules' of objects' physical behavior and constraints upon that behavior. These principles are considered to constitute a core foundation to our understanding of material bodies that persists through adulthood (Carey & Spelke, 1994; Spelke, 1991).

But this is not the only explanation on offer. A very different view holds that before 9–12 months of age, infants have no appreciation of object principles; rather, infants' performance in experiments investigating object knowledge can be accounted for in terms of low-level perceptual expectations rather than a principled understanding of physical objects (e.g. Bogartz, 1998; Cohen, 1995; Haith, 1998). It has been suggested, for example, that when an observed object is subsequently occluded by a screen, a visual iconic memory trace of the object remains. When the screen drops to reveal no object behind it, this creates a visual effect as if the object suddenly, spontaneously 'poofed' out of existence; infants respond with heightened looking in this situation simply because they have never seen objects behave in such a way, *not* because they expect objects to maintain an enduring existence (Haith, 1998).[1] On another proposal, infants' longer looking, in habituation paradigms, to situations involving apparent object impermanences is simply a response to superficial perceptual similarities and differences in the habituation and the test displays, combined with individual preferences for familiarity versus novelty, not a response to the impermanence itself (e.g. Bogartz, 1998; Bogartz, Shinskey & Speaker, 1997). Similar arguments have been made not only about infants' appreciation of the principle of continuity, but also about their understanding of solidity. It has been proposed that only at 12 months of age do infants come to appreciate this property of objects (Cohen, 1995; Cohen, Gilbert & Brown, 1996; see also Haith, 1998). Again, apparent findings to the contrary in younger infants are accounted for, by these researchers, in terms of low-level sensory or perceptual preferences. On this class of proposals, then, infants' looking times in existing experiments putatively testing for object knowledge do not reflect understanding of object principles (such as the expectation that objects endure, or that objects are solid entities that cannot pass through each other). Rather, infants' looking times are understood to reflect visual preferences resulting from previous visual experience, be it experience obtained 'naturally' in the life of the infant, or experience provided in the habituation phase of an experiment.

A third position recently delineated (Meltzoff & Moore, 1998) appeals to the persistence of mental representations in memory to explain the successes of infants under 9 months old in looking time experiments testing object permanence; genuine knowledge of object permanence is only credited to infants 9 months old and beyond. On this theory, while infants' representations of objects persist even after those objects are gone from view, infants younger than 9 months cannot reason about objects' behavior. Rather, in experiments such as those described above, infants are not evidencing any expectation that an object will continue to exist when out of sight, but are simply (a) expecting an object to be seen *again* in a location in which an object was recently seen (without any expectations or beliefs as to the state of the object between the two sightings), and (b) expecting an object to be seen at a future point along a trajectory specified by its current or recent motion (again, without any expectations or beliefs as to the existence of the object at intermediate, occluded points of the trajectory).

Both kinds of alternative view differ from the object principles view in an important respect. The object principles view posits a domain-specific body of knowledge that applies selectively to discrete, bounded, cohesive material entities – that is, to individual physical objects. On the alternative accounts, infants' performance should not be so restricted. On the 'sensory/perceptual' alternative, infants' observed looking time preferences should apply equally to any and all visual

[1] It should be noted that there are problems with this account. Critically, visual iconic memory traces are considered to last on the order of milliseconds, perhaps up to half a second; yet infants have responded to object impermanences across numerous experiments with occlusion durations ranging from about 3 to well over 15 s (e.g. Koechlin, Dehaene & Mehler, 1998; Simon, Hespos & Rochat, 1995; Wynn, 1992; Wynn & Chiang, 1998; Xu & Carey, 1996), and even, in some experiments (Baillargeon, DeVos & Graber, 1989) of 70 s! Thus, Haith's account would require a major rewriting of our theory of iconic memory, as there are no theoretical reasons or experimental evidence to date suggesting that iconic memory traces endure over these considerably longer durations.

contours (whether or not belonging to an object) seen under similar conditions; on the 'persistence of mental representations' alternative, infants' observed expectations should apply equally to any and all portions of matter (whether or not constituting an object) seen in a particular location or following a particular trajectory.

In this article, we report a series of experiments that use *collections* of objects to examine infants' object knowledge, and in particular their understanding of the continued existence of an object under occlusion conditions. Results from these experiments support the claim that infants' expectations apply selectively to cohesive, unitary physical objects, in accordance with the object principles view and in contrast to both classes of alternative.

2. Overview of the experiments

In each experiment, 8-month-olds were familiarized with the experimental setup and stimuli and then given alternating presentations of test events involving 'Expected' versus 'Magical' disappearances of an item (either a single object or a collection of small objects). An object or collection was viewed in the display, manipulated briefly, and then on some trials moved behind a screen, and on other trials moved out of the display. The screen then dropped to reveal nothing behind it (a Magical Disappearance on 'moving-behind-screen' trials, and an Expected one on 'moving-out-of-the-display' trials). Looking times to these events were compared. It is well documented that infants tend to look longer at a novel or unexpected display than at a familiar or expected display (Bornstein, 1985; Spelke, 1985). Therefore, if infants detect the violation of spatiotemporal continuity in the Magical Disappearance events, they should look longer at that event than at the expected event.

Experiment 1 established a contrast between infants' expectations about a single object versus a comparable-sized collection of smaller objects. While infants reasoned successfully about the single object, they failed to do so for the collection. Experiment 2 explored whether emphasizing the distinct individual unity of each object within a collection would help infants to represent and reason about the individual objects in the collection. Experiment 3 asked whether infants' ability to reason about a group of objects is improved if infants first view the objects as spatially separated entities, rather than grouped together in a pile. Finally, Experiment 4 asked whether prior experience with the objects making up the collection would enable infants to reason about them successfully.

3. Experiment 1

Experiment 1 investigated whether 8-month-old infants can track a collection of five identical objects as well as a single object; that is, whether infants have the same expectation about the spatiotemporal continuity of a single object and the objects *within* a collection. To test this, we used a 'two-screen' (or 'split-screen') procedure similar to that of Spelke and Kestenbaum (1986) (see also Wynn & Chiang, 1998; Xu & Carey, 1996). In this method, infants first observed the manipulation of a test item, either a single object or a collection of objects. Next, they were presented with alternating test events in which the test item (on the right side of the display) was moved either behind a screen or out of the display, and then the screen dropped to reveal nothing behind it. This outcome is consistent with the 'moving-out-of-the-display' action (i.e. the item undergoes an 'Expected' disappearance); it is inconsistent with the 'moving-behind-screen' action (i.e. the item undergoes a 'Magical' disappearance). If infants can track the item and expect it to maintain spatiotemporal continuity, they should look longer at the Magical Disappearance event than at the Expected Disappearance event.

3.1. Method

3.1.1. Subjects

The subjects were 36 healthy full-term 8-month-old infants (17 males and 19 females, mean age 8 months 0 days, range 7 months 19 days to 8 months 12 days). Eighteen of the infants were tested in the Object Condition and another 18 were tested in the Collection Condition. Seventeen additional infants were tested but excluded from statistical analyses because of failure to complete at least four test trials due to fussiness or extreme disinterest (13 infants), experimenter error (two infants), equipment failure (one infant), or an excessive looking preference (more than 2.5 SD from the group mean) for one of the two test events (one infant). Subjects were identified through birth announcements in a local newspaper and their parents were contacted by telephone. Parents' consent was acquired prior to infants' participation in the experiment.

3.1.2. Apparatus and stimuli

All experimental events took place on a yellow puppet stage measuring 101 (width) × 58 (height) × 22 cm (depth). The stage was placed on a long table with the stage floor 22 cm above the table surface. Two identical-looking screens were attached to the front of the stage, which could be rotated upward to partially occlude the stage. Each screen (23.5 cm wide, 18.5 cm high) was approximately 19 cm from the nearer side wall of the stage and 15 cm from the other screen. A grid of light orange lines was drawn on the back to provide visual interest and to camouflage two trapdoors located on the back wall of the stage. With the screens raised, the trapdoors were hidden from the infant's view. When raised, the sides of the screens facing the infant were white, contrasting with the yellow back wall. There was an opening on each side of the stage, through which the experimenters could move and manipulate the test items with their hands. A black curtain in front of the stage could be lowered to conceal the entire stage between trials. A hidden video camera above the stage recorded the subject's activities during the experiment; another camera located behind the infant recorded the experimental presentation. Black curtains were attached to each side of the stage in order to make the display salient and to conceal the experimenters. Two lights lit the stage from above. Two additional lights hung from the ceiling lit the infant indirectly. There were no other light sources in the room during the experiment.

Infants sat in an infant seat on the table facing the stage about 90 cm away, with their eye-level 20 cm above the floor of the stage. Parents sat behind the infant, out of his or her range of vision, and were instructed not to interact with their baby. A background observer monitored the experiment. A primary observer was hidden behind the curtain on one side of the display and watched the infant through a peephole on the curtain; this observer could not see the display stage and was blind to the order of test trials. The observer measured the subject's looking times by operating a button box which was connected to a computer. Once the infant had looked for a minimum of 0.5 s at the outcome, each test trial ended after the infant either looked away for 2 s consecutively, or looked at the outcome for 30 s cumulatively. Two additional experimenters were located behind the stage, one to present the overt events to the infants (the 'presenter'), and one to perform surreptitious actions through the hidden trapdoors. The presenter could view the infant through a peephole to ensure the infant was attending to the events.

The test items used in the Object Condition were two three-layer pyramids constructed of blue Lego blocks (base area 4.8 cm^2, height 3.0 cm). The items used in the Collection Condition were two collections, each consisting of five blue Lego blocks ($1.6 \times 1.6 \times 2.0$ cm each). With the five blocks piled together, the overall shape and size of the pile was similar to that of the Lego pyramid.

3.1.3. Design and procedure

Infants were randomly assigned to the Object Condition or the Collection Condition.[2] Prior to the experiment, infants were presented with and encouraged to touch the experimenter's hands in long white gloves; they were subsequently led into the testing room. After being introduced to the display stage, each infant was presented with two familiarization and then six test trials alternately depicting an event sequence in which an entity (an object or a collection) was placed behind the right-most screen, and a sequence in which the entity was removed from behind the right-most screen and taken out of the display (see below for a full description). The order of events was fixed for each subject but counterbalanced across subjects – half of the subjects received the 'moving-behind-screen' trial first and the other half received the 'moving-out-of-the-display' trial first. In the test trials, both kinds of event sequences concluded with the same outcome – the right-most screen dropped to reveal nothing behind it. In the familiarization trials, no final outcome was shown; the screen remained raised, occluding the space behind it.

In all trials, a second, identical entity (object or collection) was located in the display behind the left-most screen. The presence of this left-most entity eliminated practical difficulties with presenting an empty stage to infants in the test trials, as a scene so lacking in visual detail might not capture their interest sufficiently to generate meaningful looking times.

[2] The performance of the infants in the Object Condition of Experiment 1 was independently reported in Wynn and Chiang (1998) as one part of a larger experiment investigating a very different issue – infants' ability to detect Magical Appearances versus Magical Disappearances.

3.1.4. Object Condition

3.1.4.1. Introduction to the stage. First, the experimenter's gloved hand appeared on the stage holding a 'Sylvester Cat' puppet and moving it from the right end to the left end and then back, exiting from the right side, to draw the infant's attention to the range of the stage. Then the infant's attention was directed to the screens, showing that things could be hidden behind the screens and would be visible between the screens. Infants were also shown that the screens could be rotated up and down and the curtain could be raised and lowered.

3.1.4.2. Familiarization trials. Infants were presented with two familiarization trials: the 'moving-behind-screen' and the 'moving-out-of-the-display' trials. For each infant, these two trials were presented in the same order as that of the test trials they received. The '*moving-behind-screen*' trial (see the left half of Fig. 1) started with one Lego pyramid on the infant's left-hand side of the stage. After it was manipulated by the experimenter manually (being picked up, turned around, and moved forward and back: this took 8 s), another identical pyramid was placed on the right-hand side of the stage, and manipulated in the same way (8 s). Next, the screens rotated upward (3 s) to occlude the left-most pyramid while the right-most one stayed visible beside the screen. The right-most pyramid was then slid along the stage floor by the experimenter's hand until it was entirely behind the screen, and the empty hand withdrew from the stage (7 s). After a short pause (2 s), the curtain was lowered to end the trial. The '*moving-out-of-the-display*' trial (see the right half of Fig. 1) started with two Lego pyramids on the stage. Each pyramid was manipulated as described above (8 s for each pyramid). Next, the screens were rotated upward (3 s) to occlude both pyramids, one behind each screen. Then the empty, open hand of the experimenter entered and reached behind the right-most screen, returned with the pyramid in view, and slid it out of the display until the hand with the pyramid was entirely out of sight (7 s). The curtain was then lowered after a brief pause (2 s) to end the trial. Infants' looking times were not measured. Thus, the events in each familiarization trial took approximately 26 s. All the manipulations and hand motions were smoothly and clearly performed throughout the experiment. In order to draw the infant's attention, the experimenter always tapped three times on the stage floor with her index finger before any critical manipulation or movement of the pyramid. The screens did not drop to reveal the outcome in the end of the familiarization trial; therefore, no direct information was provided about what to expect in the outcome of the test trials. Test trials followed the familiarization trials immediately.

3.1.4.3. Test trials. The test trials were similar to the familiarization trials, with two differences. First, in each trial the experimenter simply tapped on the stage floor beside the left-most pyramid three times to draw the infant's attention instead of manipulating it, in order to shorten the presentation (4 s). Second, at the end of each test trial, the screens dropped to reveal just the left-most pyramid resting on the stage, with no object behind the right-most screen. The observer measured the

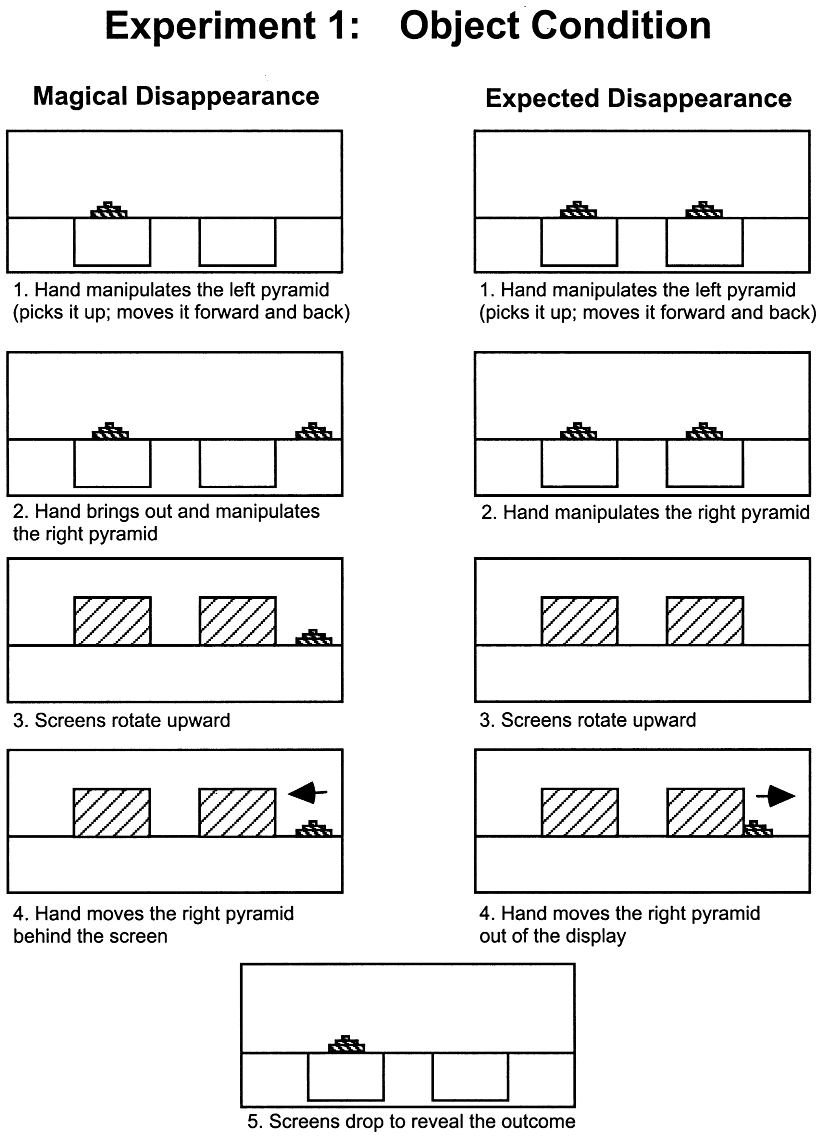

Fig. 1. Sequence of test events and the outcome presented to infants in the Object Condition of Experiment 1. Trials alternated between Magical Disappearance and Expected Disappearance events.

infant's looking times to the outcome. In the 'moving-behind-screen' trial, a second experimenter opened the trapdoor, secretly took away the object arriving behind the upward screen, and closed the trapdoor before the screens were dropped to reveal the outcome. In the 'moving-out-of-the-display' trial, the second experimenter again reached into the display through the trapdoor to reduce any unwanted procedural differences between the two kinds of trials (of course, there was no pyramid to be removed in these trials). Therefore, infants saw a 'Magical' disappearance in the 'moving-behind-screen' trials and an 'Expected' disappearance in the 'moving-out-of-the-display' trials. Test events thus took about 22 s before the outcome was revealed.

In both familiarization and test trials, the presenting experimenter viewed the infant to ensure the infant was attending to the event sequences, talking to get the infant's attention if his/her gaze wandered during presentation. If the infant was judged not to have seen the critical aspects of the event (the placement of the object behind the screen or removal from the display), the black curtain was dropped, and the trial was repeated.

3.1.5. Collection Condition

3.1.5.1. Introduction to the stage. The same as in the Object Condition.

3.1.5.2. Familiarization trials. The familiarization trials in this condition were similar to those in the Object Condition, with some changes due to the change of stimuli. In this condition, two collections of five blocks were used. The '*moving-behind-screen*' trial (see the left half of Fig. 2) started with a collection of five blocks piled together (with four blocks forming a base and one block on top) on the infant's left-hand side of the stage. The collection was then manipulated as follows. The component blocks were first moved from the pile one at a time to form a line on the edge of the stage, showing that they were distinct objects, and then scooped back together into a pile (14 s). Next, a second collection was introduced to the display – the experimenter's hand slid a pile through the opening on the right side of the stage – and manipulated as described above (14 s). The rest of the procedure was identical to that of the Object Condition. The screens rotated upward to occlude the left-most collection while the right-most collection stayed visible beside the screen; the right-most collection was slid by the experimenter's hand until it was entirely behind the screen and the empty hand withdrew from the stage, and then the curtain was lowered after a brief pause to end the trial. The '*moving-out-of-the-display*' trial (see the right half of Fig. 2) started with two collections present on the stage. Next, the left-most collection was manually manipulated by the experimenter from the left, and then the right-most collection from the right. Again, the rest of the procedure was identical to that of the Object Condition. Thus, each familiarization trial took approximately 38 s.

3.1.5.3. Test trials. As in the Object Condition, the test trials differed from the familiarization trials in two respects. The experimenter simply tapped the stage floor beside the left-most collection three times instead of manipulating it (4 s), and the screens dropped at the end of each trial to reveal just the left-most collection on the stage. Test events thus took about 28 s before the outcome was revealed.[3]

[3] Experiment 3 below alleviates possible concerns that the greater length of the event sequences for the Collection Condition than the Object Condition negatively influenced infants' performance.

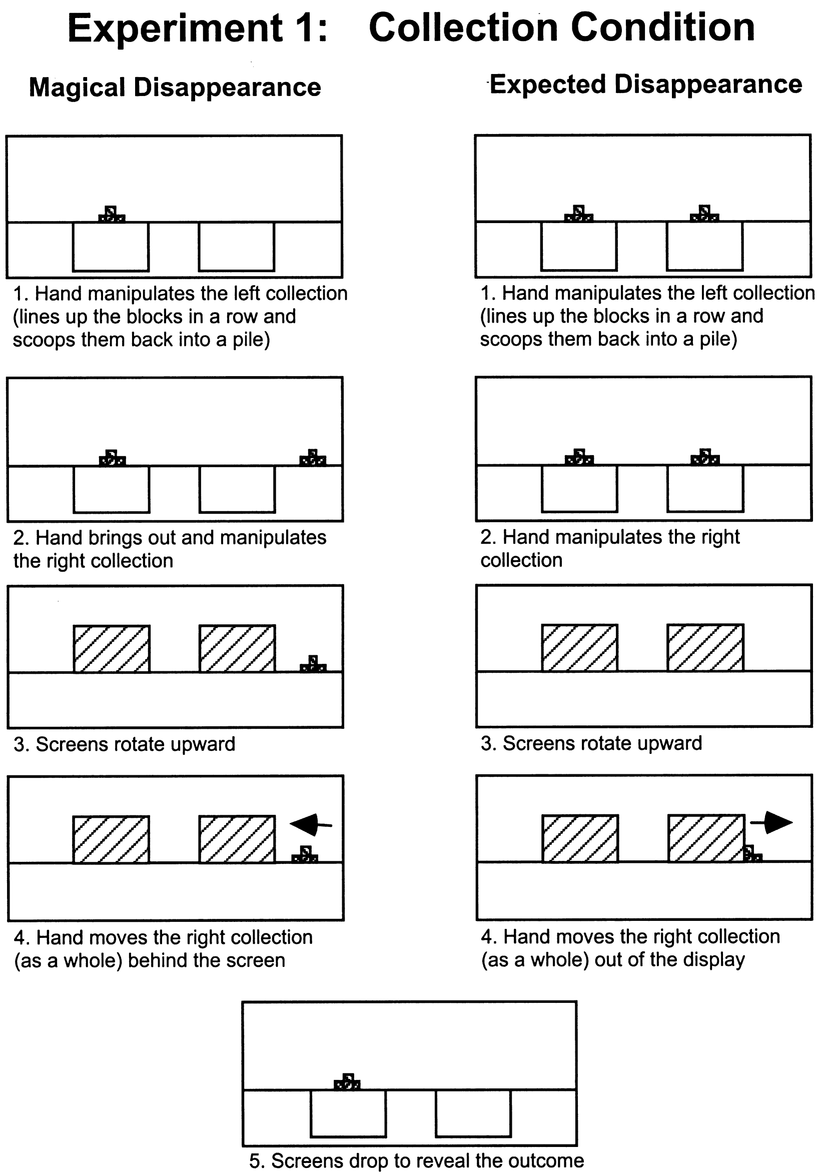

Fig. 2. Sequence of test events and the outcome presented to infants in the Collection Condition of Experiment 1. Trials alternated between Magical Disappearance and Expected Disappearance events.

3.2. Results and discussion

A 2 × 2 ANOVA on infants' mean looking times to the two events, with Condition (Object versus Collection) as a between-subjects factor and Test Event (Magical versus Expected Disappearances) as a within-subjects factor, revealed a significant Condition × Test Event interaction ($F(1, 34) = 5.38$, $P < 0.05$). Post-hoc *t*-tests on the looking preference of each group indicated that infants in the Object Condition looked reliably longer at the Magical (10.1 s) than Expected Disappearances (7.5 s) ($t(17) = 2.69$, $P < 0.01$, one-tailed), while in contrast, infants in the Collection Condition looked equally at the Magical (6.3 s) and the Expected Disappearances (6.6 s) ($t(17) = -0.35$, $P > 0.6$, one-tailed) (see Fig. 3).

The results show that infants in the Object Condition detected the violation of spatiotemporal continuity (i.e. the Magical Disappearance), indicating that they are able to track a single object and expect it to move in a continuous path. However, infants in the Collection Condition did not detect the violation of continuity in the Magical Disappearance trials.

Some conclusions can be drawn from these findings. First, as many previous infant studies have shown, infants well under 1 year of age are able to reason about single, medium-sized objects – they can track a solid, cohesive object and expect it to exist continuously when it moves out of view. Second, when a *collection* of objects is

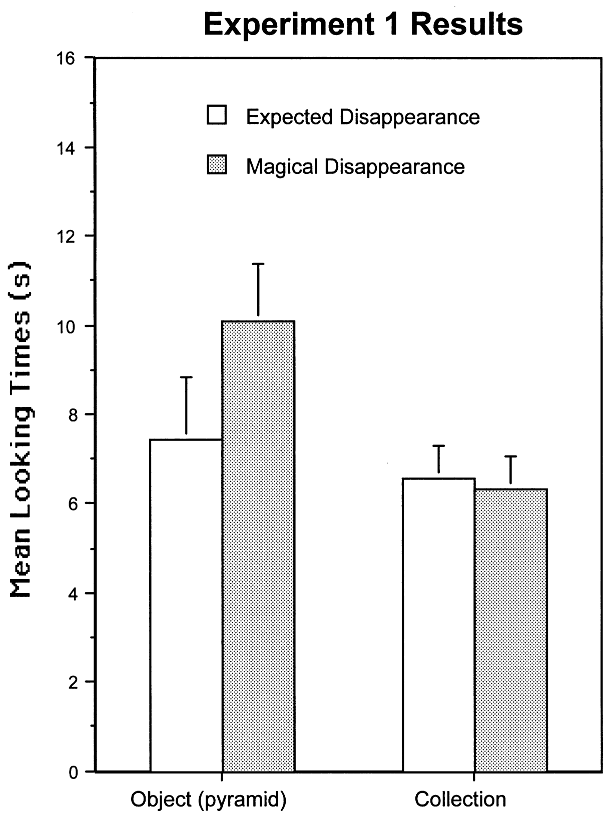

Fig. 3. Infants' mean looking times and standard errors to Magical versus Expected Disappearances in the Object and Collection Conditions of Experiment 1.

presented in a similar experimental situation, it appears that infants' object knowledge is not applied if the collection was first shown in a congregated pile, perceptually resembling a cohesive object. This suggests that infants did not construe the collection as 'multiple objects', because if they did so, they should presumably have shown heightened looking preference for these objects' Magical Disappearance.

Third, the current findings suggest that infants' expectation of object permanence does not derive from some low-level perceptual capacity, as suggested by some researchers (e.g. Bogartz, 1998; Cohen, 1995; Haith, 1998). In this experiment, both our pyramid-shaped object and our pile were of the same overall shape, size, and color; both were moved in precisely the same manner, pushed by the hand either behind the screen or out of the display. Yet infants responded very differently in the two conditions, showing an expectation of continuity for the single cohesive object, but not for the pile that violated cohesion. Infants do not apply expectations of spatiotemporal continuity to any and all contours or portions of matter in their visual field. These results are also at odds with the theory (Meltzoff & Moore, 1998) that below 9 months of age, infants' looking times in experiments testing for object permanence result simply from the persistence of mental representations in memory. On this account, if something is seen in a specific location (or seen to be following a given trajectory), infants will expect to see it again in the same location (or to see it continuing along some extrapolated future segment of the trajectory). This cannot account for infants' success in detecting the Magical Disappearance of the single object – in the unexpected trials, infants did not actually see the object in the location behind the screen, hence could not have been indicating an expectation to see it *again* at that location. Moreover, along with perceptual explanations of infants' performance, this account provides no basis for infants' differential treatment of a single object and a similarly-shaped pile, when these two entities behave in a similar fashion. Our findings are, however, consistent with the object principles view of infants' object knowledge. On this view, infants' knowledge applies selectively to discrete, cohesive, bounded entities. Our pyramid was such an entity; accordingly, infants expected it to observe continuity. Our pile, in contrast, was not such an entity; its rearrangement into a line of separate components manifested a non-cohesive structure of the whole. Accordingly, no expectation of continuity was applied to it.[4]

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[4] Subsequent experiments ruled out two possible reasons for infants' failure in the Collection Condition. First, it might be asked whether infants have difficulty in reasoning about objects as small as those used in the collection; perhaps they were too small to engage infants' object knowledge. In a separate experiment with the same apparatus, stimuli and procedures, 8-month-olds were presented with Expected and Magical Disappearances of a single small object. Infants looked significantly longer at the Magical (7.5 s) than at the Expected Disappearance (5.8 s) of the single object ($t(16) = 1.88$, $P < 0.05$, one-tailed) (reported as part of Experiment 1 in Wynn & Chiang, 1998). Second, it might be asked whether infants have difficulty in tracking an entity that does not maintain rigid boundaries during motion; in the Collection Condition of Experiment 1, the individual objects in the pile shifted relative to each other as the pile was slid behind the screen/out of the display, so the pile moved in a non-rigid fashion. In a separate experiment with the same stimuli and similar apparatus and procedures, 8-month-olds were presented with a pile that maintained a rigid shape during its displacement behind the screen or out of the display. Infants showed the same pattern of results, again looking equally at the Expected (7.9 s) and Magical Disappearance (8.6 s) of the collection ($t(13) < 1$, one-tailed).

4. Experiment 2

The results of Experiment 1 indicate that infants have difficulty tracking collections but not single objects. In Experiment 2, we emphasized the individual object identity of each block within the collection to see if this would help infants to apply their object knowledge to the individual objects that constituted the pile. This was achieved by moving the collection out of sight *one object at a time* after it was lined up. The facts that (a) adults tend to organize a display of multiple objects moving together into a perceptual unit in accordance with the Gestalt principle of common fate (Bloom, 1996; Braddick, 1980; Wertheimer, 1923), and (b) that infants tend to use relative motion among surfaces to individuate a display into distinct units (e.g. Kellman & Spelke, 1983; von Hofsten & Spelke, 1985) suggest the possibility that removing the cue of common motion of he blocks while adding that of independent motion may motivate infants to represent the collection as 'multiple objects', and thus lead them to detect the Magical Disappearance of the component objects.

4.1. Method

The method was the same as that in the Collection Condition of Experiment 1 with the exception of the points noted below.

4.1.1. Subjects

The subjects were 14 healthy full-term 8-month-old infants (eight males and six females, mean age 8 months 4 days, range 7 months 28 days to 8 months 14 days). Three additional infants were excluded because of failure to complete at least four test trials due to fussiness.

4.1.2. Procedure

There were three changes in the procedure from that of the Collection Condition of Experiment 1. First, at the start of each trial in the familiarization and in the test, two collections of piled up blocks were visible in the display upon the raising of the curtain, with the right-most collection located between the right-most screen and the side wall of the stage (see Fig. 4). Second, during the manipulation, the blocks were spread out in a line as in Experiment 1 (8 s) *but were not regrouped back into a pile*. In order to shorten the duration of the test events, the left-most collection underwent this pile-to-line transformation only in the familiarization trials; in the test trials, the left-most collection was presented as a line throughout each trial. Third, after being lined up, the right-most collection was then moved by the experimenter's hand one block at a time behind the screen or out of the display (15 s total). The hand was always open with the palm facing the infant to show its emptiness when it entered the display and when it withdrew from the back of the screen. Test events took about 30 s before the dropping of the screens.

4.2. Results and discussion

Fig. 5 presents the mean looking times to the two kinds of events. The infants

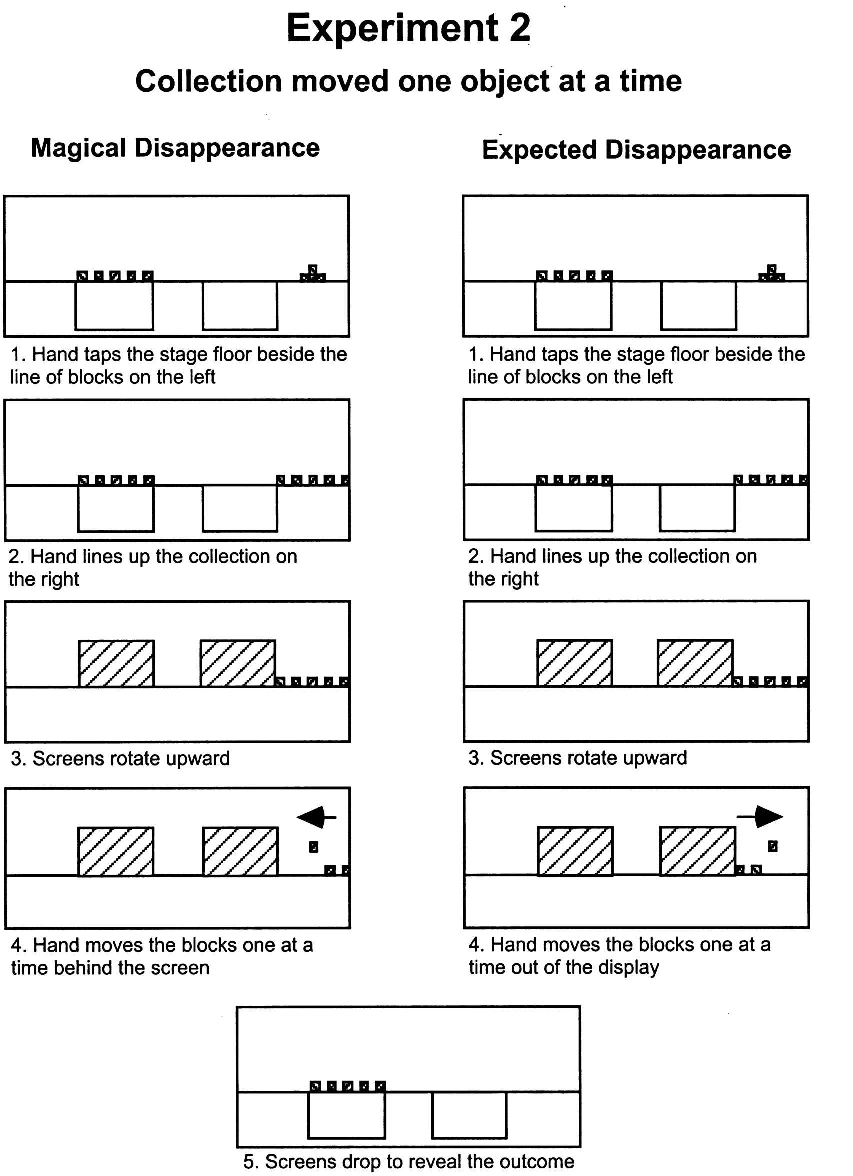

Fig. 4. Sequence of test events and the outcome presented to infants in Experiment 2. Trials alternated between Magical Disappearance and Expected Disappearance events.

looked equally at the Magical (6.2 s) and Expected Disappearance (7.0 s) ($t(13) < 1$). That is, even when the objects in the collection were moved *one at a time* behind the screen, infants did not expect them to endure once out of sight.

It is known that infants rely heavily on motion cues in object individuation (e.g.

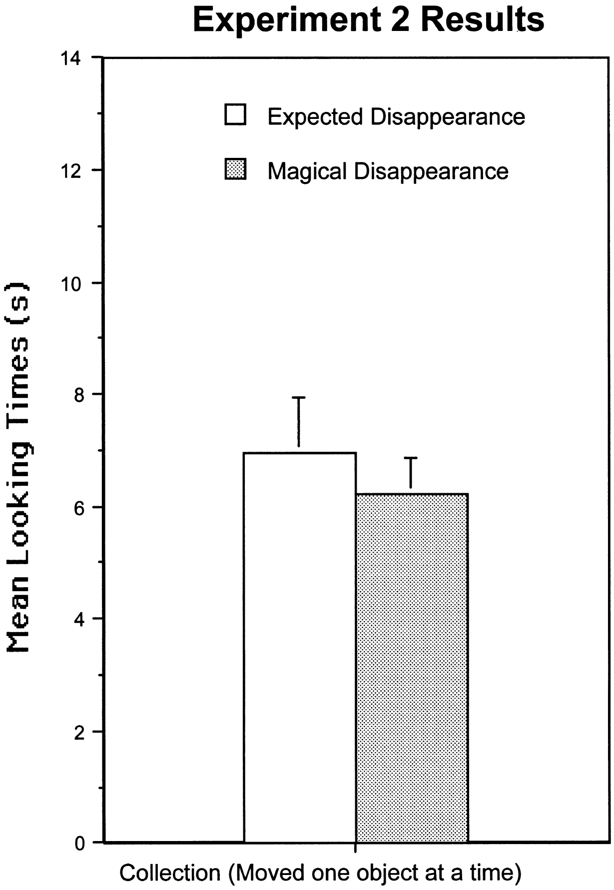

Fig. 5. Infants' mean looking times and standard errors to Magical versus Expected Disappearances in Experiment 2.

Kellman & Spelke, 1983; von Hofsten & Spelke, 1985). It is thus surprising that the procedural changes in Experiment 2 did not draw the infants' attention to the individual objects which they are capable of tracking – the independent motion of the blocks within a collection did not prompt infants to form a 'multiple objects' representation.

One possibility is that infants may be unable to follow the rearrangement in the configuration of the collection at the perceptual level in the three experiments. The visual transformation from pile (with a single visual contour evident) to line (with distinct contours for each block visible) may confuse infants or disrupt their object-tracking process. A second possibility relates to the number of objects in the collection. Five objects may be more than infants can simultaneously keep track of, and this representational overload might result in infants tracking none of the objects. A third possibility concerns infants' object representation. The pile-to-line transformation may have provided information that prevented infants from representing the component parts of the collection as 'objects' and tracking them. That is, infants may have initially misconstrued the pile as a 'single object' due to its single visual contour and homogeneous color and texture; its subsequent 'disassembly' (i.e. the spreading-out manipulation), violating the cohesion principle, may have either led infants to assign a non-object status to both the pile and its constituent elements (perhaps viewing it as an infinitely decomposable portion of substance), or have disrupted an object-tracking process already in progress operating over the entire pile. Experiment 3 was designed to test these possibilities.

5. Experiment 3

Experiment 3 tests whether infants' failure in reasoning about our collections in previous experiments results from the number of objects, the complexity of the pile-to-line transformation, or an initial misconstrual of the pile of objects as a single unitary object in itself. One critical step was added to the procedure. In contrast to Experiments 1 and 2, infants initially saw the five objects *lined up in a row* rather than in a pile, and only after this were they piled together and manipulated as in Experiment 2 – the pile was then spread into a line (the 'pile-to-line' transformation) and each block was moved separately behind the screen (a Magical Disappearance) or out of the display (an Expected Disappearance). In other words, this experiment presented infants with a 'line-to-pile-to-line' transformation of the collection before it disappeared from view. The predictions are as follows: if infants in our previous experiments failed to apply object knowledge to the members of the collection because they had difficulty in processing the pile-to-line transformation, or if their difficulty results from the number of objects, they should fail in this experiment as well, since the same transformation is performed, and the same number of objects is used. Alternatively, if infants' failure in tracking resulted from initially misconstruing the pile as an 'object' and then having difficulty interpreting the subsequent non-cohesive 'dismantling' of the pile, then in this experiment initially seeing the blocks separated, each with its own distinct contour, should facilitate the correct construal of each of the constituents as an object in its own right and so lead infants to successful performance.

5.1. Method

The method was the same as that in Experiment 2 with the exception of the points noted below.

5.1.1. Subjects

The subjects were 14 healthy full-term 8-month-old infants (six males and eight females, mean age 8 months 0 days, range 7 months 23 days to 8 months 13 days). Eleven additional infants were excluded from this experiment because of failure to complete at least four test trials due to fussiness or extreme disinterest (nine infants), experimenter error (one infant), or because of reaching the maximum looking criterion (30 s) in more than two pairs of test trials (one infant).

5.1.2. Procedure

The procedure was identical to that of Experiment 2 with the exception that at the start of each trial (both familiarization and test), after the curtain was raised, two collections of lined-up blocks were revealed, a row of five objects on the right-hand side of the stage, and a row of five objects on the left-hand side of the stage. The blocks were then piled together (6 s) and, following the procedure of Experiment 2, spread out into a line again (8 s). Subsequently, the blocks on the right side were moved one at a time behind the raised screen or out of the display (15 s). Test events took about 36 s before the screens dropped to reveal the outcome.

5.2. Results and discussion

Fig. 6 presents the mean looking times to the two kinds of events. A t-test indicated that infants looked longer at the Magical (6.1 s) than the Expected Disappearance (4.4 s) ($t(13) = 2.13$, $P < 0.05$, one-tailed).

In contrast to the results of Experiment 2, the current results show that infants are able to track a collection and detect the Magical Disappearance, indicating that infants' failure in previous experiments cannot be attributed to the length and complexity of the experimental events or to the number of objects in the collection. Results of this experiment suggest that infants' difficulty in previous experiments had to do with the fact that in their first exposure to the collection, the blocks were all together in a single pile. If the objects in the collection are initially presented so that they are clearly discernible, with the distinct contour of each element fully visible, infants respond to the Magical Disappearance of the collection as an unexpected event.

6. Experiment 4

In Experiment 4, we ask whether infants' immediate perceptual experience of the objects, just prior to their movement behind the screen or out of the display, is what determines infants' success or failure. Perhaps if infants first see the blocks in a pile in which they overlap and create a single visual contour (as in Experiments 1 and 2), this forces an 'object' construal of the pile, in which infants' perceptual and/or conceptual processes automatically engage to track the pile as a single object. When the pile is subsequently disassembled into its component pieces during the 'pile-to-line' transformation, these processes may not be able to 'regroup' and develop an alternative construal in time to generate accurate predictions about the scene. Alternatively, infants' perceptual and conceptual processes may be more flexible than this. Prior knowledge of the nature of our stimuli may enable them to interpret the pile as composed of individual objects, even if in the experiment itself it initially takes the form of a single-contour pile.

There is evidence that prior experience can, in some cases at least, affect infants'

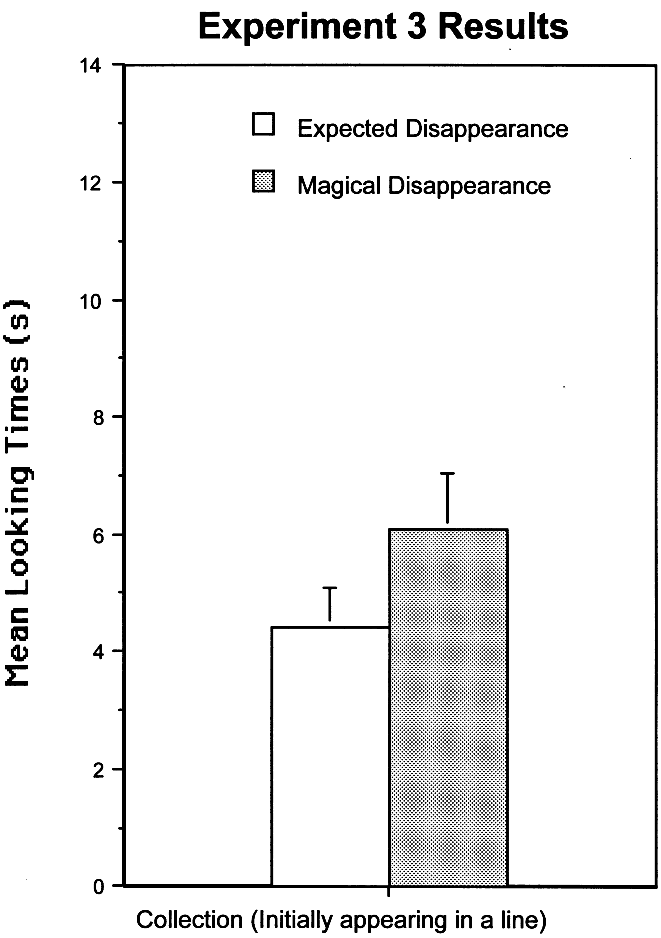

Fig. 6. Infants' mean looking times and standard errors to Magical versus Expected Disappearances in Experiment 3.

object segregation. In experiments by Needham and Baillargeon (1998), when 4.5-month-old infants saw a yellow cylinder and a blue box next to and touching each other, they showed no expectations as to whether the display comprised one or two objects. However, when shown the box alone prior to seeing the whole display, infants formed a 'two-object' interpretation of the display. Thus, experience with our blocks prior to the experiment might similarly help infants to subsequently construe our pile correctly. However, the visual characteristics of our pile of blocks differ from those of Needham and Baillargeon's display, in which the two objects had different colors, shapes and textures, and the distinct contour of each was clearly discernible. Thus, their display might have been perceptually ambiguous between one and two objects, allowing infants to identify the correct interpretation when prior information was available. In our display, the pile is homogeneous in color and texture, and the individual contours of the elements are not clearly discernible; rather, the only clear contour evident is the overall one of the pile. The current experiment asks whether infants' perceptual and object-tracking systems are rigidly forced into treating such a visual element as a single object, or whether prior knowledge can influence the treatment of a visual element.

6.1. Method

The method was the same as that in the Collection Condition of Experiment 1 with the exception of the points noted below.

6.1.1. Subjects

The subjects were 14 healthy full-term 8-month-old infants (eight males and six females, mean age 8 months 0 days, range 7 months 16 days to 8 months 12 days). Seven additional infants were excluded from this experiment because of failure to complete at least four test trials due to fussiness or extreme disinterest (five infants) or experimenter error (two infants).

6.1.2. Procedure

The only change in the procedure from that of the Collection Condition of Experiment 1 was that prior to the experiment proper, and in a separate room, each infant was presented with a pile of five blocks (the same as those used in the experiment) on a rectangular white tray and encouraged to manipulate them (for about 10 s). Approximately 30 s later, infants were brought into the experimental room. The experiment then proceeded exactly as in the Collection Condition of Experiment 1, in which infants were presented with alternating test events showing Expected and Magical Disappearances of a collection of objects which was initially presented in a pile, then spread out into a line, regrouped, and moved as a whole either behind the screen or out of the display.

6.2. Results and discussion

Fig. 7 presents the mean looking times averaged across three test pairs. A *t*-test indicated that infants looked longer at the Magical (7.8 s) than at the Expected Disappearance (5.2 s) ($t(13) = 2.69$, $P < 0.01$, one-tailed).

In contrast to the results from Experiment 1, infants successfully detected the Magical Disappearance of the collection, suggesting that infants' prior visual and manual experience with the objects influenced their interpretation of the pile in the experiment itself – they were able to view it as composed of multiple individual objects. This suggests that the immediate perception of an entity with a bounded shape and homogeneous color and texture does not automatically force a 'single object' construal of that entity. Prior experience can influence infants' construal of a scene.

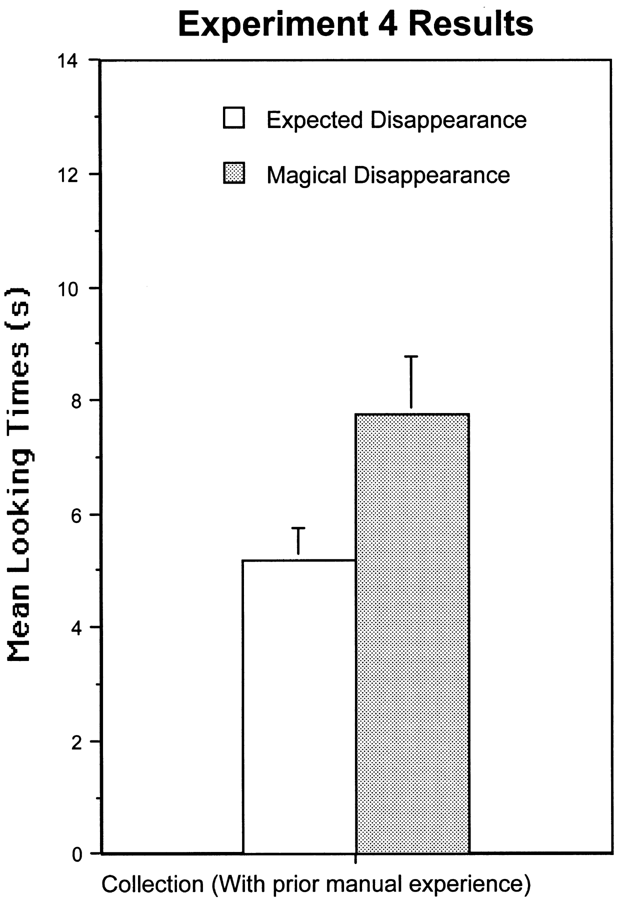

Fig. 7. Infants' mean looking times and standard errors to Magical versus Expected Disappearances in Experiment 4.

7. General discussion

In these experiments, we have presented a limitation in 8-month-old infants' ability to reason about physical objects. While they respond to the discontinuous disappearance of a single object as an unexpected event, they do not so respond to that of a group of objects, if the objects in the group are first presented piled together so that they form a single contour. While the failure we have reported shows limitations to infants' competence in reasoning about physical objects, we believe it also reveals that this competence is, in some respects, highly sophisticated. Our results support the conclusion that 8-month-olds' system of object knowledge does not apply to any and all perceptual contours or portions of matter in their visual field, but rather, applies very specifically to cohesive material bodies. This finding is clearly incompatible with proposals that success in experimental situations like ours, by infants under 9–12 months of age, can be accounted for in terms of low-level sensory/perceptual processes (e.g. Bogartz, 1998; Cohen, 1995; Haith, 1998), or by the persistence of mental representations (Meltzoff & Moore, 1998). Such proposals all predict that below these ages, infants' observed looking preferences will apply equally to any and all visual contours or portions of matters. Instead, our findings support the object principles account of infants' expectations of object behavior. Not only the perceptual characteristics, but also the behavior of an entity (e.g. whether it acts in a cohesive manner or not), influences whether infants' system of object knowledge will be applied to that entity. Moreover, infants' prior experience and background knowledge can influence the application of this system in a given situation – it is not rigidly activated by some strictly perceptual 'triggering' conditions. The notion of an 'object' appears to be a conceptually laden one, even in early infancy.

7.1. Possible sources of the difficulty

One possible explanation for infants' failures in Experiments 1 and 2 is that they conceived the collection as a non-object entity, possibly because of the non-cohesiveness of the pile that was evident when the objects were spread out into a line. Construing an entity as 'not an object' may block the application of object principles (such as the principle of spatiotemporal continuity), preventing infants from applying this principle to the collection. In contrast, in Experiments 3 and 4, infants were provided with information that allowed them to successfully construe each of the component parts of the collection as an object in its own right, allowing them to successfully reason about the individual blocks in these collections. A second possibility is that infants' performance results from limitations in the functioning of their object-tracking processes. We discuss these possibilities below.

7.2. A collection is not an object

7.2.1. Collections construed as 'non-solid substances'

As discussed earlier, the initial perception of the collection as a pile in our Experiments 1 and 2 might have led infants to misconstrue the collection as a 'single object' due to its bounded shape and homogeneous color and texture. The subsequent 'disassembling' of the pile, which demonstrated the non-cohesive nature of the collection as a whole, may have led infants to construe the component parts of the collection as portions of non-solid substance that can be further divided into smaller portions (i.e. an infinite divisibility), unlike solid objects. Infants' failure to reason about the collections in Experiments 1 and 2 is similar to infants' responses to non-solid substances – infants of the same age do not readily detect the discontinuous disappearance of a portion of sand as an unexpected event (Huntley-Fenner & Carey, 1995). Infants may have failed in these experiments because they may lack a rich understanding of how non-solid substances behave.

7.2.2. Collections construed as 'non-object individuals'

The conceptual construal of a collection of objects can focus on the individual constituents, without reference to the collection as a whole. But a collection can also be construed as an individual entity in its own right. At this level of analysis, the behavior of a collection is critically different from that of a single object. Consider, for example, a flock of birds – a collective entity that adults and children can view as an individual unit, distinct from the individual birds within it. A flock does not always maintain a rigid boundary as it moves, and individual birds or groups of birds can leave or join the flock during flight (a violation of the *cohesion* object principle). Two flocks can pass through each other (a violation the *solidity* object principle). Moreover, a flock can temporarily cease to exist when, say, the birds disperse for the evening but recollect into a flock the next morning (a violation of the *continuity* principle). Thus, a collection of objects need not obey the principles that constrain the behavior of each of its parts. One way in which to explain our results, then, would be that infants construed the collections in Experiments 1 and 2 as individual non-object entities, and therefore did not apply the principle of continuity to the collection.

Some initial studies suggest that infants can construe collections as individuals in their own right. When habituated to a particular number of groups of entities moving about on a computer screen, infants subsequently look longer at displays containing a new number of groups than at displays containing the habituated number of groups, even when the total number of individual entities is held constant, suggesting that infants treated each group as a countable individual (Wynn, Bloom & Chiang, unpublished data). Studies clearly show that adults and older children can construe collections as non-object individuals. They can track, count, and label a variety of collective entities. For example, studies of apparent motion show that perceptual cues can lead people to view collections as individuals (Braddick, 1980), and studies by Bloom and colleagues show that adults and children construe groups of objects as individuals in word-learning situations (Bloom & Kelemen, 1995; Bloom, Kelemen, Fountain & Courtney, 1995), and can use intentional cues to view collections as individuals. When given evidence that an experimenter construes a group as an individual, children are more likely to construe the group as an individual entity themselves (Bloom, 1996). Moreover, there is evidence that infants have some understanding of agency and can 'read' intentional cues (e.g. Gergely, Nadasdy, Csibra & Biro, 1995; Leslie, 1982, 1984; Woodward, 1995), which opens up the possibility that such cues might lead infants, in the right circumstances, to identify a collection as a meaningful individual. It is thus possible that infants did not detect the discontinuous disappearances of collections in our experiments because the manipulations of the collection by the experimenter led them to view the collection as a non-object individual in its own right, to which the object principle of spatiotemporal continuity did not apply.

A related possibility is that infants both represented the collection as a whole as a non-object individual, and represented the component elements as 'objects', but were unable to attend to both of these levels of representation simultaneously. Studies show that young children have difficulty in actively maintaining a dual representation. For example, it is hard for them to simultaneously think of a photograph both as a representation of objects in reality, and as an object in its own right (DeLoache, 1987; DeLoache & Marzolf, 1992). It is thus possible that the dual representation of both the non-object whole and the object parts presented similar problems to infants.

7.3. Object-tracking processes in infants

One approach to understanding infants' knowledge of objects is to characterize it as resulting from the operation of cognitive processes that, by virtue of their inherent structure, implicitly embody certain aspects of object behavior in the way that they function. Rather than being understood as resulting from limitations on infants' understanding of non-solid substances, or their inability to simultaneously maintain active representations of both the object parts and the non-object whole of the collection, an alternative possibility is that infants' failure in our Experiments 1 and 2 may result from limitations in the functioning of their *object-tracking mechanism*.

Studies of visual attention have suggested that such object-tracking mechanisms exist in adults (Kahneman, Treisman & Gibbs, 1992; Pylyshyn, 1989; Pylyshyn & Storm, 1988; Tipper, Brehaut & Driver, 1990). For instance, in the theory proposed by Kahneman and colleagues (Kahneman & Treisman, 1984; Kahneman et al., 1992), object individuation and tracking are accomplished by utilizing 'object files'. On this theory, the processing of a stationary scene produces a set of 'object files' or temporary, episodic representations of objects in the scene. Each file specifies the current location of its object, and may contain additional information about the object as well, such as its size, color, the kind of thing it is, and so on. This information is updated as the object changes, moves, or goes briefly out of view. From moment to moment, current sensory information is assigned to preexisting object files when possible, to overcome perceptual discontinuities caused by events such as temporal occlusions or saccades. This system is therefore responsible for giving us the perception of continuity of object identity over time and through space – it provides the basis upon which we are able to construe a given object as the very same object observed in preceding moments.

Object-tracking processes may be present in early infancy, underlying their ability to represent object permanence in the face of full occlusion. Moreover, these processes may provide a basis for explaining why infants failed to track the objects in our collections in certain situations. When the collection was first seen by infants in a piled-up form (Experiments 1 and 2), infants may have initially represented the pile as a 'single object' based on the static, configural information; the object-tracking system would then open a single object file for that 'object', addressed by a single location in space. The subsequent disassembly of the pile into distinct pieces, each with its own distinct contour and distinct location in space, would require the system to assign the new information of multiple locations to the single preexisting object file. This 'updating' process would fail because of an intrinsic feature of the object file system – a single object file cannot be simultaneously addressed by multiple locations. To successfully resolve this situation would entail the destruction of the object file for the pile, and the simultaneous construction of five distinct new object files, one for each object. To accomplish this may require more time and/or information than was available to the infants in our experiments. More generally, in conditions where the operation of object files is uncertain, infants may be unable to keep track of the identity of the objects perceived, and thus fail to detect unnatural discontinuities such as the Magical Disappearance in our experiments. In contrast, when infants were first presented with a collection of five spatially separated objects (as in Experiment 3), or given prior experience to enable them to correctly construe the pile as composed of multiple objects (Experiment 4), the object-tracking system may have opened distinct object files to begin with, allowing infants to keep track of the objects within the collection and to detect their Magical Disappearances.[5]

The principle of cohesion may thus be built into the functioning of the object-tracking mechanism – entities which violate cohesion disrupt the process. Other principles of object knowledge can also be seen as arising out of the functioning of these processes. For example, Wynn and Chiang (1998) describe how the object-tracking system might both embody the principle of spatiotemporal continuity, and account for an interesting asymmetry found in infants' detection of violations of this principle. While infants detect the Magical *Disappearance* of an object, they do not so detect a Magical *Appearance*.

Yet, if this approach is the right one to take it must be emphasized that while the object-tracking system may in some sense be a component of the visual system, still it is not a purely perceptual process. Results of Experiment 4 suggest that background knowledge may influence how object files are assigned in a particular scene – infants with prior experience with our stimuli were able to interpret the pile as composed of several distinct objects, rather than as a single object in and of itself. Thus, object identification and tracking processes do not appear to constitute an encapsulated system, but allow for significant top-down influences.

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[5] There is evidence (e.g. Trick and Pylyshyn, 1994) that people are strictly limited in the number of objects that can be tracked at any one time (four or fewer); this suggests a limit on the number of object files that can be assigned at a given time (see Kahneman et al., 1992). How, then, can this explanation account for the fact that infants in our Experiments 3 and 4 successfully tracked the objects in the displays, given that there were five objects to each collection and two collections in the display? For infants to succeed at our task, fewer than five objects from the right-most, moved pile would need to be tracked; tracking even just one of the five objects would be sufficient, as its presence behind the screen would be then expected and its absence noted in the Magical Disappearance. But what if an infant assigned all available object files to objects in the other (left-most) pile (recall that the left-most pile was manipulated first of the two) – would the infant then be unable to assign even the requisite single file to an item in the right-most pile? A crucial aspect of the object files theory (see Kahneman et al., 1992) is that the assignment of object files is continually changing. Files are frequently de-assigned to one object in order to be reassigned to another object; as old objects exit a visual scene, new objects enter, and the tracking priorities of the visual system change. Thus, infants' performance in our experiments is consistent with this object-tracking account – infants would be able to reassign some or all of their object files to objects in the right-most pile, when those objects in turn were manipulated.

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