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Seven-month-old infants chunk items in memory

Mariko Moher *,[1], Arin S. Tuerk [1], Lisa Feigenson

Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, MD 21218, USA

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ABSTRACT

Although working memory has a highly constrained capacity limit of three or four items, both adults and toddlers can increase the total amount of stored information by "chunking" object representations in memory. To examine the developmental origins of chunking, we used a violation-of-expectation procedure to ask whether 7-month-old infants, whose working memory capacity is still maturing, also can chunk items in memory. In Experiment 1, we found that in the absence of chunking cues, infants failed to remember three identical hidden objects. In Experiments 2 and 3, we found that infants successfully remembered three hidden objects when provided with overlapping spatial and featural chunking cues. In Experiment 4, we found that infants did not chunk when provided with either spatial or featural chunking cues alone. Finally, in Experiment 5, we found that infants also failed to chunk when spatial and featural cues specified different chunks (i.e., were pitted against each other). Taken together, these results suggest that chunking is available before working memory capacity has matured but still may undergo important development over the first year of life.

Introduction

Thinking about things that are not directly perceptually accessible requires memory. Although both infants (Bauer, 2007; Oakes & Bauer, 2007; Rovee-Collier, 1999) and adults (Squire, 2009; Tulving, 2002) can store durable memory representations over long periods of time, they also must have access to a form of memory that can create and manipulate representations rapidly and on the fly. Working

* Corresponding author. Fax: +1 617 495 3728.
E-mail address: mmoher@wjh.harvard.edu (M. Moher).

[1] Current address: Department of Psychology, Harvard University, Cambridge, MA 02138, USA.

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memory, which allows for the temporary storage of information, has been shown to serve this role across the life span (Cowan, 1997; Oakes & Bauer, 2007). A hallmark of working memory is its highly limited capacity, whereby only a few items can be represented at any given time. However, adults, children, and even 14-month-old toddlers have been shown to mentally reorganize—or "chunk"—information in working memory, thereby increasing the total amount of remembered material. Here we asked whether this type of chunking of items is also available to younger preverbal infants whose working memory has not yet matured to adult-like capacity.

Working memory capacity limits during infancy

From early in life, infants represent hidden objects in memory, an ability critical to learning about the world. Consider the everyday challenges infants face, such as watching a favorite toy become covered by a blanket and seeing one's mother disappear into another room. To lift the blanket and retrieve the hidden object or to crawl after a parent, infants must rely on representations stored in memory. Laboratory tasks have demonstrated that infants can represent such absent or occluded objects. For example, 5-month-olds who saw a doll hidden behind a screen and then saw another doll added behind the same screen looked longer when the screen was lifted to reveal unexpected outcomes of one or three dolls than at the expected outcome of two dolls (Wynn, 1992). Because the two dolls were never shown simultaneously during the hiding event, this looking preference suggests that infants maintained a representation of the first object in memory and then mentally updated it to reflect the addition of the second object (see also Feigenson, Carey, & Spelke, 2002; Koechlin, Dehaene, & Mehler, 1997; Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999).

The representations that allow infants to remember a toy hidden under a blanket, or to represent the outcome when two dolls are serially hidden, need not reside in working memory. For example, these could be long-term representations with greater longevity and robustness. However, one piece of evidence suggesting that infants may rely on working memory in tasks like (Wynn, 1992) comes from the striking cases in which infants fail to remember. Across a variety of paradigms, adults have been shown to concurrently represent a maximum of only three or four visual items over brief durations (e.g., Alvarez & Cavanagh, 2004; Broadbent, 1975; Cowan, 2001; Luck & Vogel, 1997; Song & Jiang, 2006; Xu, 2002; Xu & Chun, 2006). This limit on the number of remembered items has been taken as a signature of visual short-term memory or working memory representations. A similar limit has emerged from tasks measuring the number of hidden objects infants can remember over durations ranging from less than a second to several seconds. In one series of studies, the memory capacity of 12- to 20-month-olds was measured by hiding varying numbers of objects in a box, allowing infants to retrieve either all or just a subset of the objects, and then asking whether infants continued searching the box for any remaining objects. When three or fewer objects were hidden and they had retrieved only a subset, infants successfully continued searching for the missing objects. However, when more than three objects were hidden, infants failed to continue searching (Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2004, 2008). These results suggest that infants can successfully represent one, two, or three hidden objects but fail to remember four or more objects.

A similar capacity limit was revealed when measuring infants' visual short-term memory (VSTM) for very briefly presented items using methods more similar to those used with adults (e.g., Luck & Vogel, 1997). In that experiment, 10- and 13-month-olds saw two flickering streams of colored squares. In the Changing Stream, one of the squares changed its color between each 500-ms flicker, while the other squares maintained their colors. In the Non-Changing Stream, all of the squares' colors stayed constant across flickers. Infants looked longer at the Changing Stream than at the Non-Changing Stream when the array contained one, two, three, or four squares, suggesting that they had maintained representations of the squares, compared these in memory, and noticed the color change. However, infants failed to look longer at the Changing Stream when the array contained six squares (Ross-Sheehy, Oakes, & Luck, 2003), suggesting that infants could not remember the features of this many items. This similarity in the capacity limits observed with 10- to 20-month-olds and with adults, spanning a range of methods, suggests that in some ways working memory capacity may be consistent across development, from durations ranging from 500 ms to the longer 4- to 8-s durations that have been demonstrated in adult working memory (Noles, Scholl, & Mitroff, 2008; Zhang & Luck, 2009).

Chunking items in memory

Although working memory is limited in the number of items it can maintain, it also appears to be flexible in terms of what can count as an item. In particular, adults have been shown to store representations not just of individual items but also of groups—or chunks—of items. Such chunking appears to expand the total amount of information that can be remembered. For example, adults might have difficulty in remembering the nine-letter sequence LAXJFKSFO yet easily remember the three-acronym sequence of airport codes—LAX (Los Angeles), JFK (John F. Kennedy), and SFO (San Francisco). Adults have been shown to chunk using knowledge about race times (Chase & Ericsson, 1981; Ericsson, Chase, & Faloon, 1980), the mathematical constant π (Ericsson, Delaney, Weaver, & Mahadevan, 2004), chess configurations (Chase & Simon, 1973), word sequences (Simon, 1974), and ordinal relations (Mathy & Feldman, 2012), all of which rely on information stored in long-term memory. Adults also can chunk using visual statistics learned during a short laboratory session. Observers showed a memory advantage for items from arrays in which particular items tended to co-occur, compared with arrays in which no such regularities were present (Brady, Konkle, & Alvarez, 2009; see also Fiser & Aslin, 2005), and were better at recalling lists containing recently learned word pairings than at recalling individually learned words (Cowan, Chen, & Rouder, 2004). In all of these cases, strong associations between individual items allowed the items to be grouped in memory, thereby creating a more efficiently stored representation.

What are the developmental origins of chunking? One possibility is that chunking is an acquired strategy learned through formal instruction. Alternatively, chunking may be a foundational memory process that emerges early without explicit training. One way to test these possibilities is to examine young children who are unlikely to have explicit control over memory strategies or to have received instruction in such strategies. This approach has shown that, like adults, 14-month-olds can increase memory via chunking. Toddlers who saw an array of four identical, equally spaced objects and then watched the experimenter hide all four objects inside a box failed just a few seconds later to remember how many objects had been hidden. That is, toddlers did not continue searching for the missing objects when four objects had been hidden and any subset of these was retrieved (Feigenson & Carey, 2003, 2005). However, when the four identical objects initially were presented in two spatially separated groups of two (e.g., two objects on the left side of a hiding location and two objects on the right side), toddlers now searched successfully (Feigenson & Halberda, 2004; Rosenberg & Feigenson, Unpublished manuscript). This simple manipulation of spatial separation apparently allowed toddlers to remember two groups, each containing two objects, in the face of their failure to remember a single group of four objects. Like adults, toddlers can use several types of information as a basis for chunking. In addition to the spatiotemporal chunking cues just described, 14-month-olds can use conceptual knowledge of familiar object kinds (e.g., two cats and two cars), perceptual similarity between objects, and shared verbal labels to chunk objects in memory (Feigenson & Halberda, 2008).

Although the above studies show that young children chunk without instruction, several questions remain regarding the origins of this ability. First, it is unclear whether children require linguistic competence in order to chunk; nonhuman animals have been shown to chunk, but only after many hundreds of training trials (see Terrace, 1987, 1991; Terrace & Chen, 1991). Although children are variable in their linguistic abilities, by the time they are 14 months old they typically comprehend and produce tens and even hundreds of words (Fenson et al., 1994). The finding that 14-month-olds can use shared novel labels to chunk objects together (Feigenson & Halberda, 2008) demonstrates that linguistic information can drive chunking. The question remains whether linguistic coding is necessary for chunking, at least in humans.

Second, it is unknown whether children younger than 14 months have access to chunking. Mounting evidence suggests that working memory capacity undergoes significant development during the first year of life. By 10 to 14 months of age, infants can remember both the existence and at least some of the features of up to three objects across a range of tasks (Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002; Rose, Feldman, & Jankowski, 2001; Ross-Sheehy et al., 2003). However, younger infants appear to have a smaller working memory capacity, at least for object features (Káldy & Leslie, 2005; Kibbe & Leslie, 2011; Ross-Sheehy et al., 2003). These studies suggest that infants' capacity for remembering the presence of hidden objects might not asymptote until approximately 10 months of age and that infants' memory capacity for the features of hidden objects may lag even further.

The finding that working memory capacity undergoes important development over the first year of life raises the question of whether chunking is available during this time of change. Chunking might not be performed until working memory has reached more adult-like capacity, at approximately 10 months of age. Alternatively, chunking might be available throughout the life span, even while working memory capacity is still increasing. Testing for the deployment of chunking in infants younger than those previously studied can help to address both this question and the question of whether chunking requires linguistic abilities.

Finally, evidence for untrained chunking in very young children is currently limited to a single experimental paradigm—manual search (Feigenson & Halberda, 2004, 2008; Rosenberg & Feigenson, Unpublished manuscript). The claim that chunking is available very early in life would be bolstered by evidence using different methods and measuring a different behavior.

The current experiments

Here we asked whether children younger than 10 months, whose working memory capacity has not yet matured, can use chunking to expand the amount of remembered information. Estimates of working memory capacity at any age will depend on the methods of the task and on the evidence taken to indicate successful storage of an item. For example, studies that test for infants' memory for an object's presence (e.g., Wynn, 1992) yield evidence that infants remember more items than do studies that test for infants' memory of particular object features (e.g., Kibbe & Leslie, 2011; Ross-Sheehy et al., 2003). In the current investigation, our goal was not to make claims about the absolute number of items 7-month-olds can remember but rather to test the influence of chunking cues within the context of a single task. That is, we asked whether infants provided with chunking cues remember more objects than infants not provided with such cues.

We tested 7-month-olds because current evidence suggests that for infants of this age, working memory capacity has not yet reached the mature three- or four-item limit (Káldy & Leslie, 2005; Rose et al., 2001; Ross-Sheehy et al., 2003), and because 7-month-olds are considerably younger than the 14-month-olds for whom chunking has already been demonstrated (Feigenson & Halberda, 2004, 2008). Our first step was to ask whether 7-month-olds can remember the presence of three hidden objects in the absence of chunking cues—a task that we predicted 7-month-old infants would fail, based on the findings reviewed earlier. We showed infants three objects sequentially hidden behind a screen and then lifted the screen to reveal either the expected outcome of three objects or the unexpected outcome of two objects.

After establishing that 7-month-olds fail to remember three hidden objects when no chunking cues were provided (Experiment 1), we asked whether providing different types of chunking cues would allow infants to succeed. In Experiments 2 and 3, we asked whether 7-month-olds would remember three hidden objects when given both spatial and featural cues to group objects into chunks. In Experiment 4, we asked whether infants would remember three hidden objects when given only spatial *or* featural cues in isolation. Finally, in Experiment 5, we asked whether infants would remember three hidden objects when spatial and featural chunking cues suggested opposing parses of the array (i.e., when spatial and featural chunking cues were pitted against each other).

Experiment 1

In Experiment 1, we first sought to establish the limits of 7-month-old infants' memory capacity within the context of our task. Although previous research has found that infants of roughly this age have difficulty in maintaining the features of more than one item in working memory (Káldy & Leslie, 2005; Ross-Sheehy et al., 2003), the limits of their ability to represent the *existence* of three objects (regardless of whether they remember the objects' features) remain unknown. Because by

5 months of age infants can remember the existence of at least two hidden objects (Kibbe & Leslie, 2011; Koechlin et al., 1997; Wynn, 1992), we began by asking whether 7-month-olds also can remember three hidden objects.

Method

Participants

The participants were 20 healthy full-term infants from the Baltimore, Maryland, area of the U.S. East Coast (10 boys and 10 girls; 5 Black or African American, 13 Caucasian, and 2 other race). Their mean age was 7 months 2 days (range = 6 months 18 days to 7 months 13 days). An additional 8 infants were tested but excluded from analysis (5 for fussiness, 1 for experimental error, and 2 for parent or sibling interference). Infants were recruited by telephone and mail, and they received a small gift (shirt, book, or stuffed toy) to thank them for their participation.

Apparatus and stimuli

Infants sat in a highchair approximately 95 cm from a black wooden puppet stage (40 cm high, 129 cm wide, and 50 cm deep). A black curtain could be lowered to cover the entire stage.

A video camera mounted within the stage provided a direct view of infants' gaze, and a wall-mounted camera behind infants captured a view of the stage. Both images were recorded digitally and viewed live in an adjacent room by a trained observer who did not know the experimental condition in which infants were being tested (the portion of the video screen showing the stage was covered during coding). An experimenter hidden behind the stage inserted objects onto the stage and removed objects from the stage, and she could observe whether infants were watching these events via a hidden television monitor.

A black foam core screen (16 cm high and 80 cm wide) with a hidden ledge (10 cm deep) was used to hide the stimulus objects. The objects were three identical green and white balls (9 cm diameter) decorated with colorful dots. Squeezing the balls produced a squeaking sound that was used to draw infants' attention to each object presentation.

Procedure

The basic procedure was the same across all experiments. Parents sat out of view behind infants and were instructed to refrain from interacting with infants. Classical music was played at a low volume throughout the experiment.

Baseline trials. To measure infants' baseline preference to look at two versus three objects, the experiment began with one two-object baseline trial and one three-object baseline trial. The same stimulus objects were used throughout the baseline and test trials. For each baseline trial, the experimenter said, "Up goes the curtain," and raised the curtain to reveal the black screen already on the stage. The experimenter made sure that infants were looking (tapping the screen if they were not) and then lifted the screen to reveal either two or three objects. Infants' looking was measured from the moment the screen was completely out of view. The objects remained in place until either (a) infants looked away for at least a continuous 2 s or (b) infants looked for a total of 120 s, as indicated by the observer in an adjacent room who pressed a button to signal the end of each trial. When each trial ended, the experimenter said, "Down goes the curtain," and lowered the curtain. For this and all subsequent experiments, whether infants saw the two-object or three-object baseline trial first was counterbalanced across infants.

Test trials. On each of the eight test trials, the experimenter said, "Up goes the curtain," while raising the curtain to reveal an empty stage. The experimenter then placed the occluding screen onto the middle of the stage. Next, she lowered a ball directly above the center of the screen, squeaked it once, and then hid it behind the screen. Throughout this object presentation, the experimenter's arm remained visible above the screen so that infants could infer the final hiding location of the ball. This procedure was repeated until three balls were hidden, at which point the experimenter lifted the screen and the measurement period began. On half of the test trials the screen lifted to reveal the expected outcome (three balls), and on the other half the screen lifted to reveal the unexpected outcome (two balls, with the third ball surreptitiously removed from the stage on the concealed ledge of the screen) (Fig. 1). On unexpected outcome trials, the remaining balls were centered behind the screen. For this and all subsequent experiments, expected and unexpected outcomes alternated across the eight test trials, with test trial order (expected outcome shown first or second) counterbalanced across infants.

All testing sessions were later recoded by two trained observers who were unaware of the experimental condition and order of trial types. Their interrater agreement averaged 95.1% across all participants. Looking times greater than 2.5 standard deviations from the group mean for that trial were replaced by the same-trial average looking times of participants in the same condition. This resulted in the replacement of 3.8% of all trials.

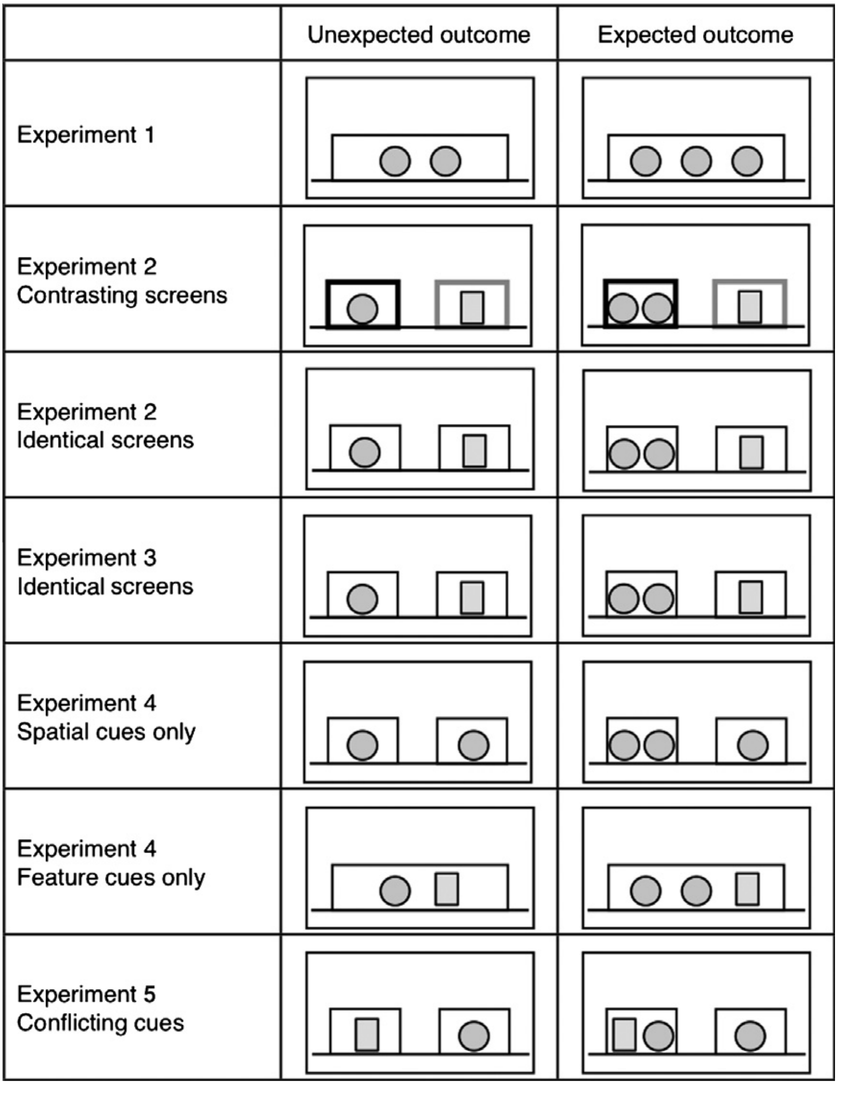

Fig. 1. Depiction of the unexpected and expected test outcomes for each experiment. The black borders around the objects depict the screens, which occluded the objects as they were being sequentially hidden and then were lifted to reveal the objects. These same arrays served as the baseline arrays within each experiment.

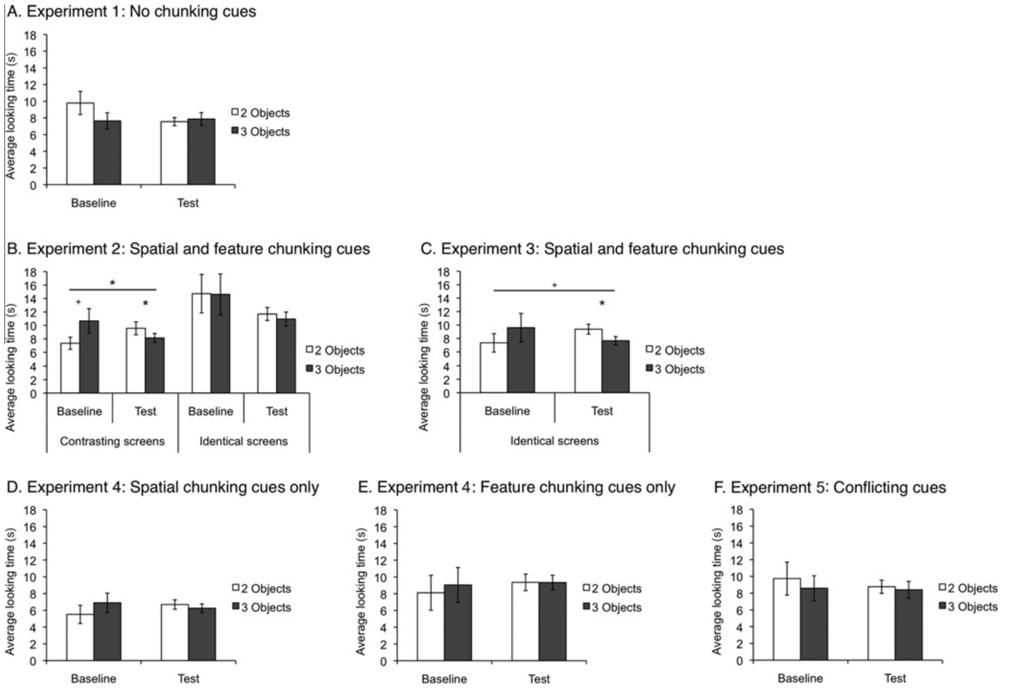

Fig. 2. Infants' average looking times to two versus three objects in the baseline and test arrays: (A) Experiment 1; (B) Experiment 2; (C) Experiment 3; (D and E) Experiment 4; (F) Experiment 5. Bars depict standard errors. $^{*}p < .05$; $^{+}p < .01$.

Results

Baseline trials

To assess infants' baseline preference to look at two versus three objects, we first analyzed looking times from the two baseline trials in a 2 (Outcome: two objects or three objects) × 2 (Trial Order: two-object array or three-object array shown first) analysis of variance (ANOVA). We observed no effect of outcome; infants exhibited no significant baseline preference for either the two-object array (9.79 s) or the three-object array (7.65 s), $F(1,16) = 1.873$, $p = .188$ (Fig. 2A).

Test trials

We next analyzed infants' looking times from the test trials in a 2 (Outcome) × 4 (Test Pair: first, second, third, or fourth) × 2 (Trial Order) ANOVA.[2] This revealed a significant main effect of test pair, $F(3,54) = 7.010$, $p < .001$, $\eta_p^2 = .280$; infants' average looking times were longer on the first three pairs (8.34, 9.05, and 7.71 s, respectively) than on the last pair (5.76 s). There was also a significant Outcome × Test Pair interaction, $F(3,54) = 3.288$, $p < .001$, $\eta_p^2 = .154$, driven by infants looking longer at the unexpected outcome on the second test pair but looking equally to both outcomes on all other pairs. No other main effects or interactions were observed. Critically, there was no significant main effect of outcome, $F(1,18) = 0.359$, $p = .557$. Averaged across the four test pairs, infants did not look longer at unexpected two-object outcomes (7.55 s) than at expected three-object outcomes (7.87 s) (Fig. 2A).

Finally, we asked whether infants' preference to look at two versus three objects in the baseline trials differed from their preference during the test trials. A 2 (Trial Type: baseline or test) × 2 (Outcome) ANOVA revealed no significant main effects or interactions.

[2] In this and all other experiments, we first analyzed the data including gender as a factor. No significant main effects or interactions involving gender emerged in Experiment 1 or in any other experiments.

Discussion

In Experiment 1, we found that 7-month-olds failed to remember three identical objects when they were hidden sequentially behind a single screen. This suggests that, in addition to their limited representation of specific object features (Káldy & Leslie, 2005; Kibbe and Leslie, 2011; Ross-Sheehy et al., 2003; Simon et al., 1995), infants of this age may also be limited in the number of object representations they can maintain in working memory, at least in the context of this task. It is an open question whether infants of this age might succeed at representing three hidden objects if the objects were hidden simultaneously rather than sequentially (for evidence that this type of "object first" presentation can improve infants' performance, see Uller et al., 1999) or if the retention interval were shortened by presenting the objects more quickly (Diamond, 1990). However, our primary interest was whether, given a constant sequence of events, providing chunking cues would improve infants' performance.

Experiment 2

By 14 months of age, toddlers can use spatial cues to chunk identical objects (Feigenson & Halberda, 2004) and can also use featural cues to chunk equally spaced objects (Feigenson & Halberda, 2008). Here, to maximize the chance that these much younger 7-month-old infants would also show successful chunking, we began by presenting infants with arrays containing both spatial and featural chunking cues. First, we spatially separated the objects into two groups by hiding them behind two different screens rather than the single screen used in Experiment 1. One object was hidden behind one screen, and two objects were hidden behind the other screen. In the Contrasting Screens condition, we further emphasized the distinctiveness of the screens by outlining the border of one screen in pink and the other in blue. In the Identical Screens condition, the two screens were identical but clearly spatially separated. Second, in both the Contrasting Screens and Identical Screens conditions, we presented objects with contrasting features. One object was a leopard-print block with a painted face, and the other two objects were the green and white balls used in Experiment 1. The number of objects hidden and the timing and duration of the hiding events were identical to those in Experiment 1.

Method

Participants

The participants were 40 healthy full-term infants from the Baltimore area, with 20 infants in the Contrasting Screens condition and 20 in the Identical Screens condition (19 boys and 21 girls; 1 Asian, 4 Black or African American, 30 Caucasian, and 5 other race). Their mean age was 6 months 29 days (range = 6 months 14 days to 7 months 15 days). An additional 10 infants were tested but excluded from the final analysis (3 for fussiness, 5 for experimenter error, and 2 for parental interference).

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 1 except for two changes. First, two smaller black foam core screens (16 cm high and 25 cm wide) replaced the single screen used in Experiment 1. In the Contrasting Screens condition, one screen had a pink border and the other screen had a blue border (1.6 cm wide) around all four sides. In the Identical Screens condition, both screens were black. Second, one of the green and white balls used in Experiment 1 was replaced with a leopard-print block (12.5 cm high, 6.5 cm wide, and 6.5 cm deep) with a schematic smiley face.

Procedure

The procedure was identical in both conditions. As in Experiment 1, infants first saw two baseline trials consisting of one two-object array and one three-object array, with order counterbalanced across infants. The curtain first was raised to reveal the two hiding screens already in place on the stage approximately 30 cm apart (so that their endpoints were separated by the same distance as the endpoints of the single screen used in Experiment 1). On the two-object trial, the two screens were lifted simultaneously to reveal one ball behind one screen and one block behind the other screen. On the three-object trial, the screens were lifted simultaneously to reveal two balls behind one screen and one block behind the other screen. The side on which the ball(s) or block appeared was counterbalanced across infants. The three-object array always contained two balls and one block (never two blocks and one ball).

Infants then saw eight test trials, as in Experiment 1. On each test trial, the curtain first was raised to reveal an empty stage. The experimenter simultaneously lowered the two hiding screens to their resting locations 30 cm apart in the center of the stage. Infants then saw two balls sequentially hidden behind one screen and one block hidden behind the other screen (with side and presentation order counterbalanced across trials). Because the block did not emit a squeak, the experimenter instead squeaked an extra ball (concealed behind the stage) each time an object was presented (whether it was a ball or a block) in order to attract infants' attention. As in Experiment 1, the test trials alternately revealed the unexpected two-object outcome and the expected three-object outcome. The unexpected outcome always contained just one ball behind one screen and one block behind the other screen, and the expected outcome always contained two balls behind one screen and one block behind the other screen (Fig. 1).

As in Experiment 1, looking times greater than 2.5 standard deviations from the group mean for that trial were replaced by the same-trial average looking times of participants in the same condition. This resulted in the replacement of 5.0% of all trials.

Results

Baseline trials

A 2 (Outcome) × 2 (Trial Order) × 2 (Chunking Cue: Contrasting Screens or Identical Screens) ANOVA revealed a marginally significant main effect of chunking cue, $F(1,36) = 3.573$, $p = .067$, $\eta_p^2 = .090$. Infants in the Identical Screens condition looked longer overall (14.66 s) than infants in the Contrasting Screens condition (9.00 s). However, there was no main effect of outcome, $F(1,36) = 1.137$, $p = .293$; infants looked equally long at the two-object array (11.03 s) and three-object array (12.64 s). There were no other significant main effects or interactions.

Test trials

We next analyzed looking times from the test trials in a 2 (Outcome) × 4 (Test Pair) × 2 (Trial Order) × 2 (Chunking Cue) ANOVA. As predicted, this revealed a significant main effect of outcome, $F(1,36) = 4.460$, $p = .042$, $\eta_p^2 = .110$. Averaged across all test trials, infants looked significantly longer at unexpected two-object outcomes (10.46 s) than at expected three-object outcomes (9.38 s) (Fig. 2B). This preference for the two-object outcome was observed both for infants in the Contrasting Screens condition (9.56 vs. 8.14 s), $t(19) = 2.329$, $p = .031$, $d = 0.591$, and for infants in the Identical Screens condition (11.69 vs. 10.94 s), although in the Identical Screens condition the preference was not statistically significant, $t(19) = 0.938$, $p = .360$. There was also a significant main effect of test pair, $F(3,108) = 3.488$, $p = .018$, $\eta_p^2 = .088$, driven by infants looking longer at the first (11.49 s) and second (10.50 s) test pairs than at the third (8.73 s) and fourth (8.96 s) test pairs, regardless of outcome. Finally, there was a main effect of chunking cue, $F(1,36) = 4.359$, $p = .044$, $\eta_p^2 = .108$, driven by infants in the Identical Screens condition looking longer across all trials than infants in the Contrasting Screens condition, regardless of outcome. There were no other main effects or interactions. The lack of an interaction between outcome and chunking cue, $F(1,36) = 0.055$, $p = .817$, suggests that infants looked longer at the unexpected outcome whether or not the hiding screens were marked by contrasting borders.

As in Experiment 1, we asked whether infants' preference to look at two versus three objects differed between the baseline and test trials. A 2 (Trial Type) × 2 (Outcome) × 2 (Chunking Cue) ANOVA revealed a significant main effect of chunking cue, $F(1,38) = 4.766$, $p = .035$, $\eta_p^2 = .111$, with infants in the Identical Screens condition looking longer across all trials (12.79 s) than infants in the Contrasting Screens condition (8.97 s). In addition, there was a marginally significant Trial Type × Outcome interaction, $F(1,38) = 3.184$, $p = .082$, $\eta_p^2 = .077$, with infants looking longer at the two-object outcome only during the test trials, when it was the unexpected result of the hiding sequence (Fig. 2B). There was no

Trial Type × Outcome × Chunking Cue interaction, $F(1,38) = 1.599$, $p = .214$, indicating that this marginal preference for the two-object outcome only during test trials was observed for infants in both chunking cue conditions.

Discussion

The results of Experiment 2 suggest that 7-month-olds successfully represented three objects in memory. When provided with multiple redundant chunking cues, including distinctive hiding locations and contrasting object features, 7-month-olds who saw three objects sequentially hidden looked longer when two objects were revealed than when three objects were revealed, in the face of their failure to do so when these chunking cues were absent (Experiment 1). To our knowledge, this is the first evidence that infants younger than 14 months may be able to expand the number of items held in memory through chunking.

Because little previous work has explored infants' ability to chunk objects, and because infants' success in the Identical Screens condition of Experiment 2 did not reach statistical significance, we wished to confirm infants' chunking abilities before exploring the particular cues underlying performance. In Experiment 3, we aimed to replicate the finding of successful chunking in a separate group of infants using the Identical Screens condition from Experiment 2 (which offered fewer chunking cues and, therefore, provided a more stringent test of replication).

Experiment 3

Method

Participants

The participants were 20 healthy full-term infants from the Baltimore area (7 boys and 13 girls; 1 Asian, 4 Black or African American, 12 Caucasian, and 3 other race). Their mean age was 6 months 26 days (range = 6 months 14 days to 7 months 14 days). An additional 7 infants were tested but excluded from the final analysis (1 for fussiness, 4 for experimenter error, and 2 for parental interference).

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were identical to those from the Identical Screens condition of Experiment 2. As in Experiments 1 and 2, looking times greater than 2.5 standard deviations from the group mean for that trial were replaced by the same-trial average looking times of participants in the same condition. This resulted in the replacement of 6.0% of all trials.

Results

Baseline trials

A 2 (Outcome) × 2 (Trial Order) ANOVA revealed no significant main effects or interactions, including a main effect of outcome, $F(1,16) = 1.738$, $p = .206$. Infants did not look significantly longer at either the two-object outcome (7.35 s) or three-object outcome (9.61 s).

Test trials

We next analyzed looking times from the test trials in a 2 (Outcome) × 4 (Test Pair) × 2 (Trial Order) ANOVA. This yielded a significant main effect only of outcome, $F(1,18) = 5.671$, $p = .028$, $\eta_p^2 = .240$. Infants looked longer at unexpected two-object outcomes (9.38 s) than at expected three-object outcomes (7.66 s) (Fig. 2C).

We also asked whether infants' preference to look at two versus three objects differed between the baseline and test trials. A 2 (Trial Type) × 2 (Outcome) ANOVA revealed a marginally significant interaction, $F(1,19) = 3.906$, $p = .063$, $\eta_p^2 = .171$. Infants preferred to look longer at the two-object outcome than at the three-object outcome, but only during the test trials when it was the unexpected result of a hiding sequence.

Discussion

Experiment 3 replicated our previous finding that 7-month-olds can use spatial and feature chunking cues to increase the amount of remembered information. As in Experiment 2, we found that infants who saw three objects hidden sequentially behind two screens looked longer at an unexpected outcome of two objects than at an expected outcome of three objects. Given that this pattern of success was not observed in Experiment 1, when no chunking cues were provided, these results suggest that infants in Experiment 3 were able to chunk representations of the hidden objects in memory.

Infants' success in Experiments 2 and 3 raises the question of which cues drove infants' chunking. In previous research, 14-month-olds have been shown to chunk on the basis of spatiotemporal cues alone (Feigenson & Halberda, 2004, 2008) and featural cues alone (Feigenson & Halberda, 2008). Therefore, in our next experiment, we asked whether spatial separation between hiding locations or contrasting object features would independently support 7-month-olds' chunking as they appear to do for older children (Feigenson & Halberda, 2004, 2008).

Experiment 4

In Experiment 4, we examined 7-month-old infants' ability to use spatial or featural cues alone as a basis for chunking. In the Spatial Cues condition, infants saw three identical objects hidden behind two identical spatially separated screens. In the Feature Cues condition, infants saw three objects, two of which had identical features, hidden behind a single screen.

Method

Participants

The participants were 40 healthy full-term infants from the Baltimore area (17 boys and 23 girls; 2 Black or African American, 33 Caucasian, and 5 other race). Their mean age was 6 months 29 days (range = 6 months 16 days to 7 months 13 days). An additional 11 infants were tested but excluded from the final analysis (3 for fussiness, 4 for experimenter error, and 4 for parental interference).

Apparatus and stimuli

Infants in the Spatial Cues condition saw three identical green and white balls (the same objects used in Experiment 1) hidden behind two identical black screens (the same screens used in the Identical Screens condition of Experiment 2 and in Experiment 3). Infants in the Feature Cues condition saw one leopard-print block and two green and white balls (the same objects used in Experiments 2 and 3) hidden behind a single large screen (the same screen used in Experiment 1).

Procedure

Infants saw two baseline trials and eight test trials that were similar to those in Experiments 1 to 3. In the baseline trials of the Spatial Cues condition, the two screens were lifted simultaneously to reveal one ball behind each screen (two-object trial) or two balls behind one screen and one ball behind the other screen (three-object trial). In the baseline trials of the Feature Cues condition, the screen was lifted to reveal one ball and one leopard-print block (two-object trial) or two balls and one block (three-object trial).

During the test trials, infants always saw three objects hidden sequentially behind the screen(s) (Fig. 1). In the Spatial Cues condition, infants saw three identical balls hidden behind two screens. The side on which two objects were hidden and whether one or two balls were hidden behind the first screen were counterbalanced across trials for each infant. In the Feature Cues condition, infants saw two balls and one block hidden behind a single screen, with the two balls always hidden in succession (ball–ball–block or block–ball–ball). Whether infants first saw the balls or the block hidden was counterbalanced across trials for each infant.

As in the previous experiments, looking times greater than 2.5 standard deviations from the group mean for that trial were replaced by the same-trial average looking times of participants in the same condition. This resulted in the replacement of 5.0% of all trials.

Results

Baseline trials

A 2 (Outcome) × 2 (Trial Order) × 2 (Chunking Cues: Spatial Cues or Feature Cues) ANOVA revealed a significant Outcome × Trial Order interaction, $F(1,36) = 4.133$, $p = .049$, $\eta_p^2 = .103$, driven by infants looking longer at the first trial they saw, regardless of whether it contained two or three objects (Trial 1: 8.86 s; Trial 2: 5.84 s). There were no other main effects or interactions. Infants did not look longer at the two-object outcome (6.81 s) or the three-object outcome (7.97 s), $F(1,36) = 0.624$, $p = .435$.

Test trials

We next analyzed looking times from the test trials in a 2 (Outcome) × 4 (Test Pair) × 2 (Trial Order) × 2 (Chunking Cues) ANOVA. This yielded a significant main effect of test pair, $F(3,108) = 3.886$, $p = .011$, $\eta_p^2 = .093$, driven by infants looking longer at the first three test pairs (8.08, 8.43, and 8.83 s, respectively) than at the last pair (6.29 s). There was also a main effect of chunking cues, $F(1,36) = 8.713$, $p = .005$, $\eta_p^2 = .187$, driven by infants in the Spatial Cues condition looking longer across all trials (9.35 s) (Fig. 2D) than infants in the Feature Cues condition (6.47 s) (Fig. 2E). However, there was no effect of outcome, $F(1,36) = 0.250$, $p = .620$. Averaged across all test pairs, infants did not look longer at unexpected two-object outcomes (8.02 s) than at expected three-object outcomes (7.79 s). This lack of a significant preference for either outcome was observed for infants in both the Spatial Cues condition (6.69 vs. 6.25 s) and the Feature Cues condition (9.36 vs. 9.33 s) (Fig. 2D and E).

We also asked whether infants' preference to look at two versus three objects differed between the baseline and test trials. A 2 (Trial Type) × 2 (Outcome) × 2 (Chunking Cues) ANOVA revealed no significant main effects or interactions. Critically, there was no Trial Type × Outcome interaction, $F(1,38) = 0.703$, $p = .407$, suggesting that infants' preference for two versus three objects did not change when these were the unexpected and expected results of an object hiding sequence.

Discussion

In previous research, 14-month-olds have been shown to chunk arrays of identical objects when provided with spatial grouping cues (Feigenson & Halberda, 2004) and to chunk equi-spaced arrays of objects when provided with featural or conceptual grouping cues (Feigenson & Halberda, 2008). The results of Experiment 4 suggest that for younger 7-month-olds, neither spatial nor featural cues are independently sufficient to support object chunking, at least in the context of the current task. Although our finding does not preclude the possibility that a single cue other than those we tested here could suffice to support chunking at this age, it does raise the possibility that these younger infants may require multiple cues in order to chunk successfully and that chunking may undergo developmental change between the 7 and 14 months of age (see General Discussion).

However, an alternative to the claim that 7-month-olds can chunk if provided with multiple cues is that infants succeeded in Experiments 2 and 3 simply because the stimulus arrays in those experiments were more perceptually interesting, thereby attracting infants' attention more strongly and making it more likely that the objects would be encoded and remembered. The stimulus arrays in Experiments 2 and 3 contained two distinctive hiding locations (demarcated by two screens) and also contained objects with high featural contrast (a smiling leopard-print block vs. spotted balls). In comparison, the stimulus arrays in Experiments 1 and 4 either contained just a single screen/hiding location (Experiment 1 and the Featural Cues condition of Experiment 4) or contained all identical objects (Experiment 1 and the Spatial Cues condition of Experiment 4). Therefore, one might worry that infants paid more attention to the arguably more complex arrays in Experiments 2 and 3 (the experiments where they succeeded) than to the simpler arrays in Experiments 1 and 4 (the experiments where they failed).

To test this possibility, in Experiment 5 we presented infants with arrays that contained exactly the same amount of spatial and featural information as in Experiments 2 and 3. Infants saw objects hidden behind two spatially separated screens and saw the same featurally contrasting objects as in Experiments 2 and 3. However, in Experiment 5 we reorganized the arrays such that spatial and featural cues no longer specified the same chunks; we hit a ball and a block behind one screen and hid another ball behind the other screen. If infants require multiple redundant cues to support chunking—that is, if spatial and featural cues must specify the same chunks—then infants in this experiment should fail to remember the three hidden objects.

Experiment 5

Method

Participants

The participants were 20 healthy full-term infants from the Baltimore area (9 boys and 11 girls; 1 Asian, 2 Black or African American, 13 Caucasian, and 4 other race). Their mean age was 6 months 29 days (range = 6 months 15 days to 7 months 13 days). An additional 11 infants were tested but excluded from the final analysis (7 for fussiness, 3 for experimenter error, and 1 for parental interference).

Apparatus and stimuli

The apparatus and stimuli were the same as those in the Identical Screens condition of Experiments 2 and 3 (two identical black hiding screens and two green and white balls plus one leopard-print block).

Procedure

In the two baseline trials, infants saw a two-object array, in which one ball was revealed from behind one screen and one block was revealed from behind the other screen, and a three-object array, in which one ball was revealed from behind one screen and one ball and one block were revealed from behind the other screen (Fig. 1).

In the eight test trials, infants always saw a sequential presentation in which one ball was hidden behind one screen and one ball and one block were hidden behind the other screen. Infants always saw the block as either the first or last object hidden, so that the two balls were always presented in temporal succession. Expected outcomes always contained two balls and one block, and unexpected outcomes always contained just one ball and one block (Fig. 1).

As in the previous experiments, looking times greater than 2.5 standard deviations from the group mean for that trial were replaced by the same-trial average looking times of participants in the same condition. This resulted in the replacement of 5.0% of all trials.

Results

Baseline trials

A 2 (Outcome) × 2 (Trial Order) ANOVA yielded no significant main effects or interactions. Infants did not look longer at either the two-object outcome (9.74 s) or the three-object outcome (8.59 s), $F(1,16) = 0.732$, $p = .403$.

Test trials

We next analyzed looking times from the test trials in a 2 (Outcome) × 4 (Test Pair) × 2 (Trial Order) ANOVA. This revealed a significant main effect only of test pair, $F(3,54) = 3.340$, $p = .026$, $\eta_p^2 = .157$. Infants looked longer on the second (9.97 s) and third (9.96 s) test pairs than on the first (7.52 s) and fourth (6.90 s) test pairs. Critically, there was no main effect of outcome,

$F(1,18) = 0.227$, $p = .640$. Averaged across all test pairs, infants did not look significantly longer at unexpected two-object outcomes (9.74 s) than at expected three-object outcomes (8.59 s) (Fig. 2F).

We also asked whether infants' preference to look at two versus three objects differed between the baseline and test trials. A 2 (Trial Type) × 2 (Outcome) ANOVA revealed no significant main effects or interactions. Importantly, there was no Trial Type × Outcome interaction, $F(1,19) = 0.243$, $p = .628$, indicating that infants' preference for two versus three objects did not change when these were the unexpected and expected results of an object hiding sequence.

Discussion

The results from Experiment 5 strengthen our claim that infants' success at remembering three objects in Experiments 2 and 3 reflects chunking. Simply presenting infants with multiple hiding locations and contrasting object features did not cause infants to remember the hidden objects. Instead, it appears that the spatial and featural cues needed to redundantly specify the same chunks in order for infants to benefit.

General discussion

Previous studies have demonstrated that 10- to 20-month-old infants can store only three or four items concurrently in working memory (Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson, Carey & Hauser, 2002; Rose et al., 2001; Ross-Sheehy et al., 2003), paralleling similar limits in adults (Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; Cowan, 2001; Feigenson, 2008; Halberda, Sires, & Feigenson, 2006; Luck & Vogel, 1997; Scolari, Vogel, & Awh, 2008; Song & Jiang, 2006; Todd & Marois, 2004; Xu & Chun, 2006; Zhang & Luck, 2008). Previous studies also have shown that toddlers, older children, and adults can increase the total amount of stored information by binding representations of individual items into chunks (Bower, 1972; Chase & Ericsson, 1981; Chase & Simon, 1973; Cowan et al., 2004; Ericsson et al., 1980; Feigenson & Halberda, 2004, 2008; Mathy & Feldman, 2012; Rosner, 1971; Simon, 1974). In the current series of experiments, we explored the developmental origins of this ability. We found that younger 7-month-olds, who are prelinguistic and whose working memory has not yet reached mature capacity, also can remember more items by chunking. This suggests that chunking may be a foundational computation—one used from infancy onward.

To recap our findings, Experiment 1 found that 7-month-olds did not remember three identical objects sequentially hidden in a single location, consistent with previous suggestions that working memory capacity is not yet mature at this age (Káldy & Leslie, 2005; Rose et al., 2001; Ross-Sheehy et al., 2003). Experiments 2 and 3 demonstrated that when infants were provided with multiple redundant chunking cues, including spatially separated hiding locations and featurally contrasting objects, they successfully looked longer when three objects were hidden and just two objects were revealed. However, Experiment 4 revealed that neither spatial separation of the hiding locations nor contrasting object features alone were sufficient chunking cues. Infants failed to remember all three objects when given either spatial or featural chunking cues individually. Finally, Experiment 5 showed that infants' performance in Experiments 2 and 3 could not be attributed to the fact that the stimuli were more perceptually complex and that spatial and featural cues needed to specify consistent chunks in order for 7-month-olds to benefit.

Many factors influence memory, making it more or less likely that observers will remember the items in a scene. For example, previous research suggests that infants are more successful at remembering objects over shorter durations (Diamond, 1990), when given sustained or repeated presentations that allow for the potential recruitment of long-term memory resources (Canfield & Smith, 1996; Sharon & Wynn, 1998), when the number of required memory updates decreased (Uller et al., 1999), when items are presented in direct succession (Feigenson & Yamaguchi, 2009), when objects are presented later rather than earlier in a hiding sequence (Káldy & Leslie, 2005), and when given with the opportunity to compare multiple objects during encoding (Oakes, Kovack-Lesh, & Horst, 2009). Here we showed that in addition to the above factors, the extent to which an object array supports chunking also affects infants' memory, with other aspects of the presentation held constant.

Our finding that 7-month-olds chunked only when given redundant cues contrasts with previous findings that 14-month-olds needed just a single cue in order to chunk. In previous research, 14-month-olds have demonstrated successful chunking when shown spatially interleaved arrays of four familiar objects such as cat, car, cat, car (Feigenson & Halberda, 2008). Because the cats and cars were not spatially grouped (i.e., identical objects were nonadjacent), spatial adjacency and featural information specified conflicting parses of the array. The finding that 14-month-olds successfully chunked when spatial and featural cues did not overlap (Feigenson & Halberda, 2008), but that 7-month-olds did not (Experiment 5 in the current study), suggests that chunking may undergo developmental change between 7 and 14 months of age, with infants becoming increasingly adept at using more subtle cues to support chunking. However, we note that the methods used to test chunking differed across the two age groups (manual search for 14-month-olds vs. violation-of-expectation looking time for 7-month-olds). Therefore, future investigations of developmental change in chunking abilities should test infants of different ages using a single paradigm.

An additional question for future work concerns the specificity of infants' object representations. Although our findings show that infants used spatial information in conjunction with featural information to remember hidden objects, it remains unknown whether infants actually remembered both types of information. Indeed, recent work suggests that infants who remember the existence of an object may remember little about the object's features (Kibbe & Leslie, 2011). This raises the possibility that infants in our experiments may have used spatial and featural cues to encode or maintain object representations but then failed to retain this featural information in memory or to use it at retrieval (see Wang & Baillargeon, 2006; Wang & Mitroff, 2009). A related question is whether, even if infants do remember spatial and featural information, they correctly bind this information in memory. For example, infants might correctly remember that there were two objects behind the left screen and one behind the right screen but may misremember which objects were where (Káldy & Leslie, 2003; Oakes, Ross-Sheehy, & Luck, 2006). More clearly characterizing the contents of infants' representations of object chunks remains a prospect for future investigation.

Finally, the role of recent experience in guiding infants' chunking remains to be explored. In particular, it is an open question whether infants' visual exposure to the baseline arrays in Experiments 2 and 3 played a role in their later chunking of the test arrays. It is possible that seeing baseline arrays, with objects grouped by spatial location and by feature, helped infants to later use these cues to chunk. The performance of infants given only test trials would bear on this question.

To summarize, our results highlight the possibility of both developmental continuity and change in early memory. Here we found evidence that 7-month-olds, whose working memory capacity is still developing, can chunk items together to increase total information storage. However, this ability appears to be somewhat fragile in these younger infants; the 7-month-olds required multiple redundant cues in order to chunk, whereas older toddlers were able to use spatial and featural cues independently. Future work should continue to characterize both these continuous and discontinuous properties of a fundamental aspect of memory processing.

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