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Infants use temporal regularities to chunk objects in memory

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ABSTRACT

Infants, like adults, can maintain only a few items in working memory, but can overcome this limit by creating more efficient representations, or "chunks." Previous research shows that infants can form chunks using shared features or spatial proximity between objects. Here we asked whether infants also can create chunked representations using regularities that unfold over time. Thirteen-month old infants first were familiarized with four objects of different shapes and colors, presented in successive pairs. For some infants, the identities of objects in each pair varied randomly across familiarization (Experiment 1). For others, the objects within a pair always co-occurred, either in consistent relative spatial positions (Experiment 2a) or varying spatial positions (Experiment 2b). Following familiarization, infants saw all four objects hidden behind a screen and then saw the screen lifted to reveal either four objects or only three. Infants in Experiment 1, who had been familiarized with random object pairings, failed to look longer at the unexpected 3-object outcome; they showed the same inability to concurrently represent four objects as in other studies of infant working memory. In contrast, infants in Experiments 2a and 2b, who had been familiarized with regularly co-occurring pairs, looked longer at the unexpected outcome. These infants apparently used the co-occurrence between individual objects during familiarization to form chunked representations that were later deployed to track the objects as they were hidden at test. In Experiment 3, we confirmed that the familiarization affected infants' ability to remember the occluded objects rather than merely establishing longer-term memory for object pairs. Following familiarization to consistent pairs, infants who were not shown a hiding event (but merely saw the same test outcomes as in Experiments 2a and b) showed no preference for arrays of three versus four objects. Finally, in Experiments 4 and 5, we asked whether infants also remembered the specific identities of the objects in each chunk. In Experiment 4, we confirmed that infants remembered objects' identities in smaller arrays that did not require chunking. Next, in Experiment 5, we asked whether infants also remembered objects' identities in larger arrays that had been chunked on the basis of temporal regularities. Following a familiarization phase identical to that in Experiment 2a, we hid all four objects and then revealed either these same four objects, or four objects of which two had unexpectedly changed shape and color. Surprisingly, infants failed to look longer at the identity change outcome. Taken together, our results suggest that infants can use temporal regularities between objects to increase memory for objects' existence, but not necessarily for objects' identities.

1. Introduction

Research has revealed surprising limits on the amount of information that can be retained over brief intervals. Adults appear able to store representations of just three or four items at a time in visual working memory (e.g., Alvarez & Cavanagh, 2004; Cowan, 2001; Luck & Vogel, 1997; Sperling, 1960), and by around 10 months of age, infants show a similar memory limit across a range of experimental paradigms (e.g., Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002; Oakes, Hurley, Ross-Sheehy, & Luck, 2011; Ross-Sheehy, Oakes, & Luck, 2003; Zosh, Halberda, & Feigenson, 2011). For example, 12- to 21-month old infants who saw two or three objects hidden in a box, then saw just a subset of those objects retrieved, correctly searched the box for the missing object(s). In contrast, infants who saw four objects hidden and then saw any subset retrieved failed to keep searching (Barner, Thalwitz, Wood, & Carey, 2007; Feigenson & Carey, 2003; Feigenson & Carey, 2005; Feigenson & Halberda, 2004). This suggests that infants were unable to maintain a representation of four hidden objects, or even just a subset of the four. Hence working

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memory in infants and young children appears to hold no more than about three items at a time.

Although working memory is constrained in adults, children, and infants, all of these populations have been shown to overcome these constraints through the use of chunking. In a chunked representation, individual items are grouped together but are still recoverable as individuals—this allows for the storage of more information in memory. For example, experienced chess players represent unified configurations of chess pieces on a game board (e.g., "Anastasia's Mate"), and can mentally "unpack" these higher-level representations into their constituent pieces. Adults can form these kinds of efficient, chunked representations using a variety of cues, including items' shared color or spatial proximity (Bower, 1972; Hitch, Burgess, Towse, & Culpin, 1996)—as well as more conceptual cues such as common category membership or semantic relatedness (Bower, Clark, Lesgold, & Winzenz, 1969; Chase & Simon, 1973; Ericsson, Chase, & Faloon, 1980; Mathy & Feldman, 2012). Recent work shows that chunking has its origins early in development. Fourteen-month old infants successfully remembered the presence of four hidden objects when the objects were presented in two spatially grouped sets of two before they were hidden, but not when these same objects were first presented in a single set of four (Feigenson & Halberda, 2004; Rosenberg & Feigenson, 2013). Like adults, 14-month-old infants can chunk using their knowledge of object categories: they remembered four total objects when an array contained two tokens of two different types (e.g., two cats and two cars), but not when the array contained four tokens of a single type (e.g., four different cats) (Feigenson & Halberda, 2008).

This research with young children shows that from early in development, working memory makes use of "snapshot" regularities. That is, when objects within an array share a common feature or spatial location that can be observed in a single glance, the objects can be represented more efficiently. However, snapshot regularities often are not available – for example, all of the objects in a scene may be unique, or may be evenly distributed in space. In such cases, is chunking possible?

A reason to suspect that it might be is that snapshot regularities are not the only source of information that may support chunking—other, more dynamic cues might also be used. For example, the frequency with which an object occurs in a local environment can be a powerful means to more efficient representation (e.g., Huffman, 1952). How reliably particular objects are seen together, the relative timing of objects' appearances, and objects' relative spatial positions are all temporal regularities that could potentially be used to create higher-order representations. Such temporal regularities are distinct from snapshot regularities in that they are unobservable from a single exposure. Instead, they must be gleaned from experiences that unfold over time. For example, an array of four evenly spaced, differently colored objects might contain no snapshot grouping cues. But if some smaller subset of the objects had previously been observed to occur together with high regularity, then this information, accumulated over time, might be useful as a basis for chunking.

Recent evidence suggests that adults can use these kinds of temporal regularities to increase the amount of information they remember from a visual scene. Brady, Konkle, and Alvarez (2009) showed adult observers eight simultaneously presented, differently colored circles for 1000 ms, after which the circles disappeared and adults were prompted to recall the color of one of them. The critical manipulation was whether, across trials, some of the colors were highly likely to appear next to each other. For some participants, particular colors often appeared together (e.g., a red circle appeared next to a blue circle on 80% of trials). For others, the color relationships were random across trials. Brady and colleagues found that within minutes, participants who observed the regularities outperformed participants who saw randomly configured arrays. They concluded that adults used the regularities that unfolded over time to compress item representations in memory, storing representations of pairs of co-occurring items more efficiently than they could store representations of two unrelated items.

Extracting regularities across events is a potentially powerful means of overcoming working memory limits in the absence of snapshot grouping cues. To achieve this, temporal regularities must be learned rapidly, and then used to encode an array with greater efficiency than if such regularities were absent or not yet learned. Previous studies show that young infants are indeed sensitive to temporal regularities in both visual and auditory stimuli (Aslin, Saffran, & Newport, 1998; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996a; Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009; see Krogh, Vlach, & Johnson, 2013 for a review). Infants can parse artificial streams of continuous speech using conditional probabilities between syllables (Saffran, Newport, & Aslin, 1996b) and can parse visual streams of sequentially presented shapes using similar information (e.g., Kirkham et al., 2002). Nine-month old infants have been shown to use the co-occurrence statistics of visual elements to extract multi-part objects from scenes containing many smaller elements; they looked longer at pairs of elements previously seen to reliably co-occur than at pairs with a lower co-occurrence (Fiser & Aslin, 2002). However, it remains unknown whether these infants used co-occurrence statistics to form new, higher order memory representations that were available for further computation, or whether infants simply preferred looking at visual elements that had been statistically associated. One way to find out is to ask whether memory is more efficient when infants are provided with temporal chunking cues than when they are not—that is, whether experiencing temporal regularities among items increases the number of items infants can store in working memory. If so, it would suggest that working memory can be efficiently organized using a wide range of information types from early in development.

Here, in six experiments, we asked whether infants use regularities in object appearances over time in order to increase working memory performance. Because previous studies investigating preverbal chunking abilities examined infants of around 13–14 months old (Feigenson & Halberda, 2004; Feigenson & Halberda, 2008; Rosenberg & Feigenson, 2013), we focused on infants of a similar age. But unlike these previous studies, which presented infants with object arrays that could be chunked in a single glance, here we tested infants' memory for arrays of evenly spaced objects that each had a unique color and shape; thus any single viewing of an array contained no information that could be used for chunking.

In Experiment 1, we first confirmed the previously observed upper limit on the number of objects infants can remember from arrays lacking chunking cues. Following a familiarization phase, infants saw four unique objects hidden behind an occluding screen. The screen was then lifted to reveal either all four objects, or only three. We found that, as predicted, infants showed no visual preference between these two outcomes: they apparently failed to remember the presence of four hidden objects, even when each object had distinctive features, and even when they had been familiarized with all of the objects before the memory test. Next we asked whether infants would successfully remember the same array if first given the opportunity to experience temporal regularities among the objects. Infants in Experiment 2a were familiarized with the same four objects from Experiment 1, but this time saw the objects in successive presentations of pairs with multiple temporal regularities: object identity was yoked such that the appearance of one particular object (e.g., red disk) perfectly predicted the appearance of another (e.g., blue cross). In addition to this co-occurrence[1] information, objects of particular shapes and colors always appeared in the same relative spatial positions (e.g., red disk on the left, blue cross on the right), and objects were always presented in the same order (e.g., red disk placed first, blue cross placed second). To preview, we found that, following this familiarization, infants now succeeded in remembering all four hidden objects. In Experiment 2b, we replicated this success, this time with the familiarization arrays containing fewer regularities. Thus in Experiments 2a and b, infants apparently used temporal regularities experienced during familiarization to create new, more efficient representations that could be deployed at test to track objects through occlusion. In Experiment 3 we further tested this interpretation: we asked whether experiencing co-occurring objects during familiarization changed infants' ability to track hidden objects, or merely enhanced their preference to see object pairs. We showed infants the same familiarization trials as in Experiment 2a, and then showed them the three- and four-object test outcomes, with no preceding hiding event. This time infants showed no preference between the test outcomes, suggesting that their performance in Experiments 2a and 2b indeed reflected their ability to remember hidden objects. Finally, in Experiments 4 and 5, we asked whether temporal regularities not only allow infants to remember more objects than they otherwise could, but also to remember the objects' features. We found that although infants successfully remembered objects' features in small, unchunked arrays (Experiment 4), they did not show evidence of remembering the features of larger arrays requiring chunking (Experiment 5). We close with a discussion of the implications of our results for understanding working memory more broadly.

2. Experiment 1: Random pairings

In Experiment 1 we asked whether infants could concurrently maintain representations of four objects in working memory. Previous findings led us to predict that infants would fail at this, but our aim here was to confirm infants' working memory limit under the same testing conditions and with the same stimulus objects that would be used throughout the rest of our experiments. First, we familiarized infants with four unique objects presented two at a time, in pairs. Critically, the object pairings were entirely random—it was not possible to predict the color, shape, or location of one object in the pair from the color, shape, or location of the other object in the pair. Following this familiarization, infants saw test trials in which all four objects were sequentially hidden behind a screen. The screen was then lifted to reveal, in alternation, the expected outcome of four objects, or an unexpected outcome of three objects, and infants' looking time was measured.

2.1. Methods

2.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months 22 days; range 12 months 9 days–13 months 14 days; 10 girls). Three additional infants participated but were excluded from analysis due to experimenter error (2), or refusal to look (1). Infants were recruited via phone and mailing lists and received a small gift for participating.

2.1.2. Materials

The four wooden stimulus objects were constructed to be distinctive in color and shape. They were: a red disk (diameter = 11.5 cm), a blue cross (11×13 cm), a green pentagon (height = 13 cm, base = 5 cm), and a yellow bowtie-shaped object (11.5×10 cm) (see Fig. 1). These objects were presented on a black puppet stage ($130 \times 43 \times 50$ cm) and could be hidden behind a black foam-core screen (57.5×23.5 cm). A black curtain was lowered in front of the stage between trials.

2.1.3. Procedure

Infants sat in a high chair or on a caregiver's lap approximately 70 cm from the puppet stage. Soft classical music played in the background to maintain infants' interest. A camera mounted within the stage captured infants' eye gaze, and a camera mounted behind infants captured the object presentation. These two views were digitally mixed and recorded in an adjacent room, where an observer who was naive to experimental condition coded infants' looking times throughout the study. Later, these looking times were re-coded offline by two experienced observers who did not know what infants were seeing on any given trial.

2.1.3.1. Baseline. First we measured infants' baseline interest in arrays containing three versus four objects. Previous work has shown that infants sometimes show a baseline preference to look longer at arrays of more objects versus fewer objects, likely due to the greater perceptual complexity of larger arrays (e.g., Xu & Carey, 1996). Because our test outcomes involved arrays of different numbers of objects, these baseline trials were important in allowing us to ask whether infants in our study would show a similar preference, and whether this starting preference changed in the Test trials.

The two Baseline trials began with the experimenter raising the curtain to reveal an occluding screen already resting on the stage. The experimenter reached into the stage from above and drew infants' attention to the screen by jingling bells she wore around her wrist. She then lifted the screen to reveal three objects in one Baseline trial and four objects in the other, with trial order counterbalanced across participants. The objects always appeared in the same equi-spaced configuration in which they would appear during the test trials. For the 3-object Baseline trial (and for *Unexpected Outcome* Test trials), one of the four shapes was chosen at random to be omitted from the array. For both the 3-object and the 4-object Baseline trials, the array remained static on the stage until infants had looked for a minimum of one second and then had looked away from the array for two consecutive seconds. When this looking criterion had been met, the observer in the next room signaled to the experimenter to end the trial by pressing a button that made a single beep, at which point the experimenter lowered the curtain over the stage.

2.1.3.2. Familiarization. On each of the 10 familiarization trials, the curtain was first raised to reveal an empty stage. Infants then saw the experimenter reach in from above and place two objects from the set of four one at a time from left to right (from the infants' perspective) onto the center of the stage, so that they were approximately 3 cm apart. The objects were never occluded. The two objects remained visible for 5 s, during which infants could freely view them as much or as little as they wanted. After 5 s the experimenter lowered the curtain over the stage and removed the objects. The object pairs were pseudo-randomized so that, across trials, each shape appeared with every other shape equally often, so that each shape appeared on the left and on the right equally often, and so that each shape was placed first or second equally often (Fig. 1, left panel). Thus, infants saw each shape 5 times, saw it placed on the left either two or three times, and saw it placed first either two or three times (counterbalanced across infants).

2.1.3.3. Test. On each of the six Test trials, the curtain first was raised to reveal an empty stage. The experimenter then reached

[1] Although co-occurrence and conditional, joint, and transitional probabilities are all distinct, these cannot be distinguished in our experimental design.

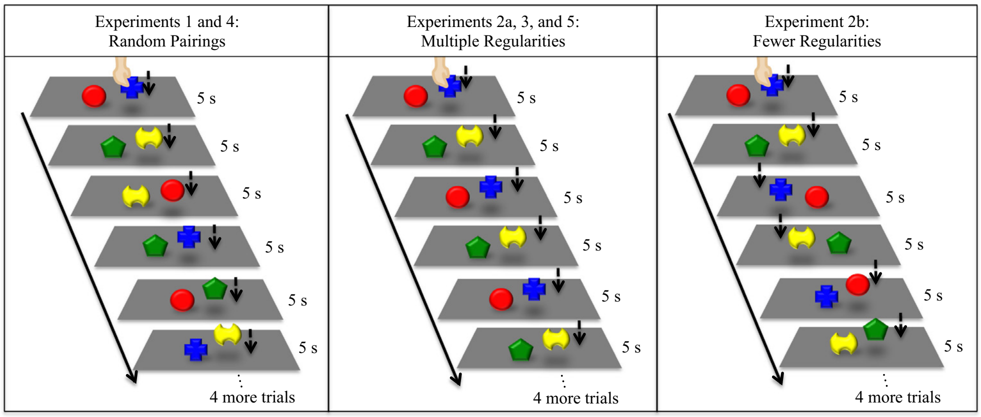

Fig. 1. Example familiarization trials from Experiments 1–5. Infants saw 10 familiarization trials. In Experiments 1 and 4, the objects were paired randomly. In Experiments 2a, 3, and 5 objects were paired with multiple sources of temporal regularities: particular object identities always co-occurred, and always appeared in the same spatial locations and the same temporal order. In Experiment 2b, fewer temporal regularities were available during the familiarization trials: particular object identities always co-occurred, but in different spatial locations and in different temporal order.

in from above and placed the occluding screen in the center of the stage. Next she placed all four objects on stage sequentially from left to right (from the infants' perspective), approximately 12 cm in front of the screen, starting with the left-most object and proceeding toward the right. Thus, infants had the opportunity to view all four objects together before they were hidden. Objects were always placed in one of two fixed orders, either disk–cross–pentagon–bowtie or bowtie–disk–cross–pentagon, counterbalanced across infants. Objects were spaced evenly 2 cm apart, so that no spatial grouping cues were present (see Fig. 2, top panel).

Once all four objects were in place, the entire array was left visible for 4 s. Then the experimenter reached down and hid the four objects behind the screen, one at a time, starting from the left. Finally, the experimenter lifted the screen to reveal either all four objects (Expected Outcome) or only three objects (Unexpected Outcome) (Fig. 2, bottom panels). For each trial with an Unexpected Outcome, a different object was chosen to be omitted from the array. Which objects were removed was counterbalanced across infants. From the time the first object was hidden to the time the test display was revealed, approximately 10 s elapsed. Expected and Unexpected Outcomes alternated three times, resulting in six total Test trials. Trial order (Expected or Unexpected Outcome first) was counterbalanced across participants.

An observer who was naive to experimental condition and trial order measured infants' looking time to each outcome. When infants had looked for a minimum of one second and then had looked away from the display for two contiguous seconds, the observer signaled the experimenter to terminate the trial. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high; mean correlation between looking times was $r = 0.94$.

2.2. Results

To correct for right skew, all data were log-transformed (Hays, 1994), a procedure often applied to infant looking time data (e.g., Spelke, Kestenbaum, Simons, & Wein, 1995; Kibbe & Leslie, 2011). We first examined infants' looking during the two Baseline trials. We found a slight but non-significant preference for four objects over three in infants' log looking times ($t_{15} = -1.11$, $p = 0.28$). Next we analyzed infants' looking during the Test trials with a 2 (Test Outcome: Expected (4 objects) or Unexpected (3 objects)) × 3 (Trial Pair: 1st, 2nd, or 3rd) repeated measures ANOVA. This revealed no main effect of Test Outcome—infants did not look longer when four objects had been hidden and only three were revealed, relative to when all four were revealed ($F_{1,15} = 1.15$, $p = 0.30$, $\eta^2 = 0.07$). The analysis did reveal a main effect of Trial Pair ($F_{2,30} = 3.54$, $p = 0.04$, $\eta^2 = 0.19$), but no Test Outcome × Trial Pair interaction ($F_{2,30} = 0.34$, $p = 0.71$, $\eta^2 = 0.02$); infants looked longer overall at earlier trials.

We then asked whether infants' looking patterns differed across the Baseline and Test trials, using a 2 (Trial Type: Baseline or Test) × 2 (Outcome: 4 objects or 3 objects) repeated measures ANOVA. There was no main effect of Trial Type ($F_{1,15} = 0.52$, $p = 0.48$, $\eta^2 = 0.03$), but there was a significant main effect of Outcome ($F_{1,15} = 4.36$, $p = 0.05$, $\eta^2 = 0.23$): infants looked longer overall at the four object arrays, regardless of whether they were presented in Baseline or Test trials. There was no interaction between Trial Type and Outcome ($F_{1,15} = 0.15$, $p = 0.71$, $\eta^2 = 0.01$); infants' pattern of looking did not change significantly between Baseline and Test trials (Fig. 3).

2.3. Discussion

The results of Experiment 1 show that infants failed to remember the presence of four hidden objects. After four objects had been hidden, infants looked no longer when only three objects were revealed than when all four were revealed. This is consistent with previous findings that infants have a representational limit of three when tracking multiple objects through occlusion (e.g., Feigenson & Carey, 2003; Feigenson & Carey, 2005; Feigenson et al., 2002). Further, although previous results showed that infants can use spatial groupings of objects to chunk (e.g., infants can represent two spatially separated groups of two but not a single group of four; Feigenson & Halberda, 2004), the results of Experiment 1 suggest that simply familiarizing infants with objects presented in successive pairs is not enough to prime them to later chunk a four-object array that lacks other chunking cues.

Next, in Experiment 2a we asked whether introducing temporal regularities into the Familiarization trials would empower infants to chunk, and thereby remember all four objects at Test. Like infants in Experiment 1, infants in Experiment 2a first saw a series of Familiarization trials in which four different objects were presented in pairs. This time, however, the objects were paired with multiple sources of temporal regularities. Object identities were yoked such that the color and shape of one object in a pair perfectly predicted the color and shape of the other object in the pair. Further, across Familiarization trials an object of a particular color and shape was always in the same spatial position relative to the

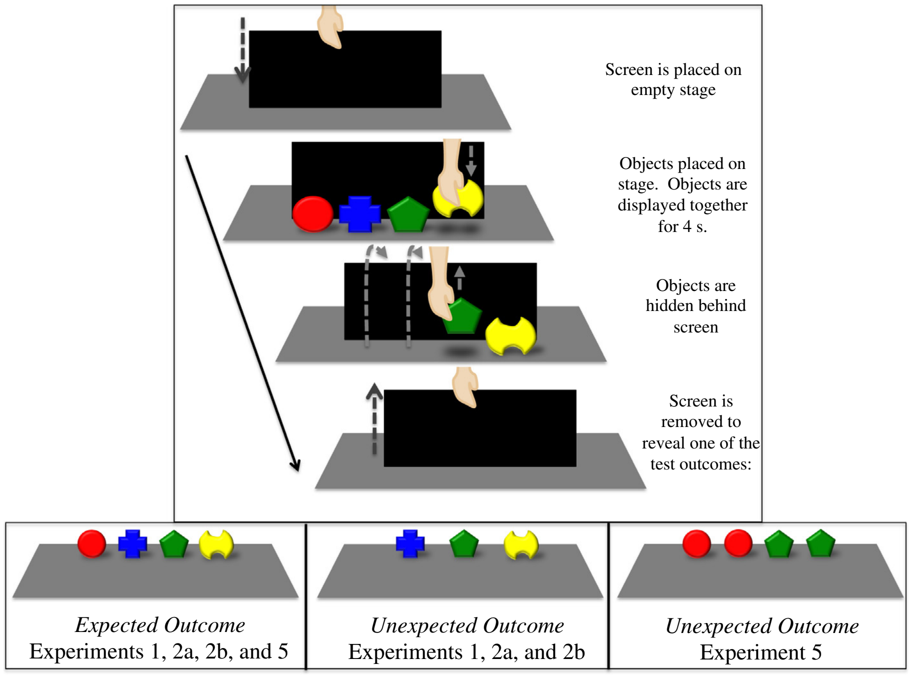

Fig. 2. Example test trials from Experiments 1, 2a, 2b, and 5. Infants in all Experiments saw the same Expected Outcome, in which the objects that were revealed were exactly those hidden. In the Unexpected Outcome trials in Experiments 1, 2a, and 2b, the number of objects was revealed to have changed. In the Unexpected Outcome trials in Experiment 5, the expected number of objects was revealed but the identities of two of the four objects had changed.

other object in the pair, and was always placed in the same relative temporal order. As in Experiment 1, after this Familiarization infants then saw all four objects hidden behind a screen, and then saw four objects or three objects revealed on alternating test trials. Thus, the only difference between Experiments 1 and 2a was the absence versus presence of temporal regularities during the Familiarization trials.

3. Experiment 2a: Multiple regularities

3.1. Methods

3.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months 25 days; range 12 months 12 days–13 months 14 days; 7 girls). Ten additional infants participated but were excluded from analysis due to fussiness (8), experimenter error (1), or parental interference (1)[2].

3.1.2. Materials

Materials were identical to those in Experiment 1.

3.1.3. Procedure

The Baseline trials were identical to those of Experiment 1.

During the Familiarization trials, infants saw four objects presented in pairs, now with multiple regularities between the objects across trials. The identities of the objects were yoked such that there was 100% reliable co-occurrence between object identities: that is, the objects were repeatedly presented in consistent pairs. Infants saw one of two possible pairings: *disk–cross*, *pentagon–bowtie* or *bowtie–disk*, *cross–pentagon*, counterbalanced across infants. Further, the objects were consistently spatially positioned relative to each other. For example, if infants were familiarized with the pair *disk–cross*, they always saw the disk on the left and the cross on the right. Finally, within each pair, the left object was always placed first (e.g., for the pair *disk–cross*, infants always saw the disk placed first). Infants saw the two yoked object pairs five times each in alternation, for a total of 10 Familiarization trials (see Fig. 1). Thus, infants received the same amount of exposure to each of the objects as in Experiment 1 (each object was presented 5 times), but the Familiarization sequence contained regularities that could be extracted across viewings.

The Test trials were identical to those in Experiment 1 (Fig. 2). The four objects first were placed in front of the occluding screen in one of two fixed orders. Whereas infants in Experiment 1 were randomly assigned to one of the two orders, infants in Experiment 2 always saw the objects placed in the same order as in the Familiarization trials. That is, if infants had been familiarized with the pairs disk–cross, pentagon–bowtie, then the objects in the Test trials were presented in the order disk–cross–pentagon–bowtie. If infants had been familiarized with the pairs bowtie–disk, cross–pentagon, then the objects in the Test trials were presented in the order bowtie–disk–cross–pentagon. The four objects were then placed sequentially behind the occluding screen, as described in the Method of Experiment 1. After all four objects had been hidden, either four objects or three were revealed on alternating trials, resulting in six total Test trials.

As in Experiment 1, infants' looking was coded in real-time by an observer in the next room who could not see what infants were seeing. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high ($r = 0.98$).

3.2. Results

Analyses were conducted on log-scaled looking times. We first examined infants' looking during the two Baseline trials. We found

[2] The attrition rates in Experiment 2a and Experiment 4 were higher than in the other experiments. While it is possible that this impacted our results, we think that this possibility is unlikely. First, the attrition rates observed in Experiment 2a and 4, while high, are within the range of attrition rates typically observed in infant looking time studies. Second, infants' performance in Experiment 2a was replicated in Experiment 2b, in which attrition was lower.

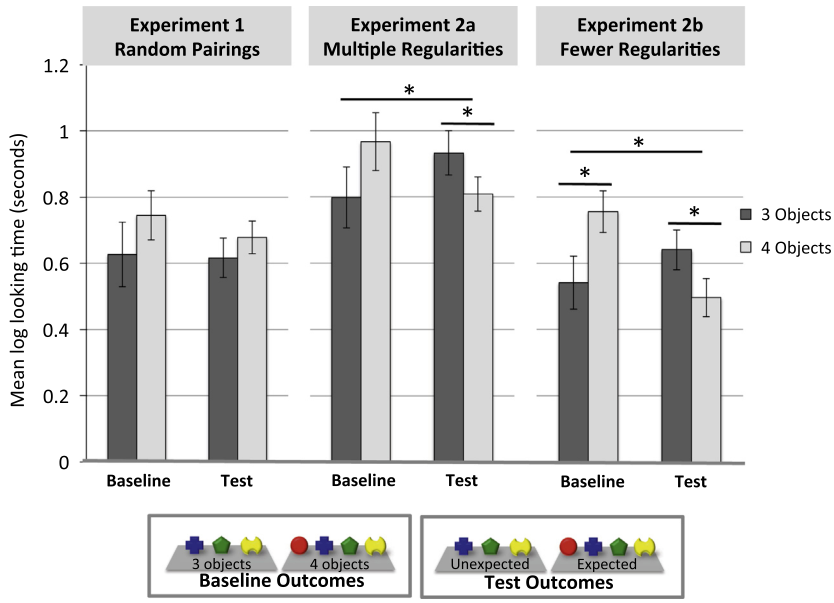

Fig. 3. Mean log looking times to the Baseline and Test trials in Experiments 1, 2a, and 2b. Baseline and Test outcomes are shown in the bottom panels. Error bars show ±1 SEM.

that infants again had a slight but non-significant preference to look at the four-object array over the three-object array ($t_{15} = -1.87$, $p = 0.08$). Next we analyzed infants' looking during the Test trials with a 2 (Test Outcome: Expected (4 objects) or Unexpected (3 objects)) × 3 (Trial Pair: 1st, 2nd, or 3rd) repeated measures ANOVA. This revealed a significant main effect of Test Outcome: infants looked significantly longer at the Unexpected Outcome of three objects than the Expected Outcome of four objects ($F_{1,15} = 4.60$, $p = 0.05$, $\eta^2 = 0.235$). There was also a significant main effect of Trial Pair ($F_{2,30} = 3.84$, $p = 0.03$, $\eta^2 = 0.20$), but no Trial Type × Trial Pair interaction ($F_{2,30} = 2.71$, $p = 0.08$, $\eta^2 = 0.15$); infants looked longer overall at the earlier test trials than the later ones.

Comparing infants' looking during Baseline to their looking during Test revealed that infants' pattern of looking to 4- and 3-object outcomes changed significantly. A 2 (Trial Type: Baseline or Test) × 2 (Outcome: 4 objects or 3 objects) repeated measures ANOVA revealed no main effect of Trial Type ($F_{1,15} = 0.03$, $p = 0.86$, $\eta^2 = 0.002$) or Outcome ($F_{1,15} = 0.29$, $p = 0.60$, $\eta^2 = 0.02$), but did reveal a significant interaction between Trial Type and Outcome ($F_{1,15} = 5.31$, $p = 0.04$, $\eta^2 = 0.26$). Infants looked longer at arrays of four objects during Baseline, but looked longer at arrays of three objects during Test (see Fig. 3).

3.3. Discussion

Infants in Experiment 2a successfully represented the existence of four hidden objects, whereas infants in Experiment 1 did not. The only difference between the two experiments was whether infants had experienced temporal regularities between the objects prior to Test. Since infants in both Experiment 1 and Experiment 2a saw the objects presented in pairs during Familiarization trials, infants' success in Experiment 2a could not simply have been due to the spatiotemporal characteristics of the Familiarization trials having primed infants to group objects into pairs. Rather, infants' success in Experiment 2a, combined with their failure in Experiment 1, suggests that experiencing temporal regularities between objects' features during Familiarization changed the way infants remembered the arrays at Test. In particular, infants had the opportunity to use the temporal regularities to represent the objects as chunked pairs, rather than as individuals. Remembering that "two chunked pairs" of objects were hidden may have been less costly for infants' memory than remembering that "four individual objects" were hidden. Critically, in order to chunk the objects in this way, infants had to represent regularities that unfolded over time across the Familiarization, since no snapshot chunking cues like shared features or spatial proximity were present in any of the arrays.

However, drawing this conclusion requires first considering other possible explanations of infants' performance. For infants in Experiment 2a, the objects' relative spatial positions during Familiarization (e.g., whether a particular object always occupied the right versus left side of the pair) always matched the objects' spatial positions observed during the Test trials. This leaves open the possibility that infants' success in Experiment 2a was driven not by chunking the objects (and therefore responding based on a memory of how many objects had just been hidden), but instead by statistically generated expectations of the objects' spatial positions. That is, even if infants had ignored the hiding of objects behind the screen on any given Test trial, they might still have expected, based on a long-term memory representation formed over Familiarization, that they should always see the red disk to the left of the blue cross, or the green pentagon to the left of the yellow bowtie. The unexpected 3-object Test outcomes would have violated such learned spatial relationships, enabling infants to respond to a violation without having tracked the objects they had just seen hidden.

In addition to ruling out this possibility, we wanted to ask whether the multiple regularities presented in Experiment 2a were all required in order for infants to chunk objects in memory. Therefore, in Experiment 2b we again familiarized infants with four objects presented in pairs, but this time we reduced the number of regularities present during the Familiarization. As in Experiment 2a, objects were yoked such that there was 100% reliable co-occurrence between object features. However, now the side and order of object placement were no longer reliable across Familiarization trials (Fig. 1, right panel). Instead, as in Experiment 1, objects could be placed to the right or left of each other, and could be placed first or second. If infants still successfully remembered all four objects in the Test trials following this Familiarization, it would suggest that infants' chunked representations are flexible: that they do not require the objects to be in a fixed spatial configuration or to be presented in a fixed temporal order. Further, such a result would rule out the possibility that infants' performance in Experiment 2a was driven by a long-term representation of the objects' relative spatial positions.

4. Experiment 2b: Fewer temporal regularities

4.1. Methods

4.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months 27 days; range 12 months 9 days–13 months 13 days; 13 girls). Two additional infants participated but were excluded from analysis due to fussiness (1) or experimenter error (1).

4.1.2. Materials

Materials were identical to those in Experiments 1 and 2a.

4.1.3. Procedure

Baseline trials were identical to those in Experiments 1 and 2a.

During the Familiarization trials, infants again saw objects presented in yoked pairs with 100% reliable co-occurrence between the objects' features. However, this time the relative spatial positions of the objects within each pair, and the order in which the objects were presented, varied across trials. For example, infants familiarized with the pair disk–cross saw the disk placed to the left of the cross on half of the Familiarization trials, and saw it placed to the right on the other half. On half of the Familiarization trials infants saw the disk placed first, and on the other half they saw it placed second (Fig. 1). Thus, although infants still experienced reliable co-occurrence between the objects' identities across Familiarization trials, the objects' relative spatial positions and the temporal ordering of their placement were no longer perfectly reliable. As in Experiment 2a, infants were randomly assigned to see one of two pairings: disk–cross, pentagon–bowtie or bowtie–disk, cross–pentagon, with the position of the objects in the pair (right or left) and order of the objects' placement on a given trial (first or second) counterbalanced across Familiarization trials.

The Test trials were identical to those in Experiments 1 and 2a (Fig. 2). As in Experiment 2a, if infants had been familiarized with the pairs disk–cross, pentagon–bowtie (with the objects' relative spatial positions and temporal ordering of placement within each pair having varied across the Familiarization trials), then the objects in the Test trial were presented in the order disk–cross–pentagon–bowtie. If infants had been familiarized with the pairs bowtie–disk, cross–pentagon, then objects in the Test trial were presented in the order bowtie–disk–cross–pentagon. Although the objects in the Familiarization trials were not presented in a fixed order, the order of objects in the Test trials was fixed to match the Test trials of Experiments 1 and 2a. Relative to infants in Experiment 2a, infants in Experiment 2b had only had about a quarter of the Familiarization exposure to the relative spatial position and temporal placement order of the object pairs as they appeared in the Test trials.

Infants' looking times were coded in real-time by an observer who could not see what infants were seeing. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high ($r = 0.98$).

4.2. Results

Analyses were conducted on log-scaled looking times. We first examined infants' looking during the two Baseline trials. We found that infants had a significant preference to look at the four-object array over the three-object array (paired samples $t_{15} = -3.64$, $p = 0.002$). Next we analyzed infants' looking during the Test trials with a 2 (Test Outcome: Expected (4 objects) or Unexpected (3 objects)) $\times$ 3 (Trial Pair: 1st, 2nd, or 3rd) repeated measures ANOVA. This revealed a significant main effect of Test Outcome ($F_{1,15} = 5.29$, $p = 0.04$, $\eta^2 = 0.26$), with infants looking longer at the Unexpected three-object outcomes. There was also a main effect of Trial Pair ($F_{2,30} = 4.09$, $p = 0.03$, $\eta^2 = 0.24$) but no Test Outcome $\times$ Trial Pair interaction ($F_{2,30} = 1.21$, $p = 0.31$, $\eta^2 = 0.08$); as in Experiments 1 and 2a, infants looked longer overall on earlier trial pairs.

Lastly we asked whether infants' pattern of looking to three-object versus four-object arrays differed significantly between Baseline and Test trials, as it did in Experiment 2a. Comparing infants' looking during Baseline to looking during Test with a 2 (Trial Type: Baseline or Test) $\times$ 2 (Outcome: 4 objects or 3 objects) repeated measures ANOVA revealed no main effect of Trial Type ($F_{1,15} = 1.57$, $p = 0.23$, $\eta^2 = 0.10$) or Outcome ($F_{1,15} = 1.03$, $p = 0.33$, $\eta^2 = 0.08$), but did reveal a significant interaction between these ($F_{1,15} = 12.88$, $p = 0.003$, $\eta^2 = 0.46$). Infants looked longer at arrays of four objects during the Baseline trials, but looked longer at arrays of three objects during the Test trials (see Fig. 3), consistent with the results of Experiment 2a.

4.2.1. Combined analyses across Experiments 1, 2a, and 2b

Infants in Experiments 1, 2a, and 2b saw identical Test outcomes. The only difference between the experiments was the way in which the objects were presented during the Familiarization trials. We therefore used a combined analysis to ask whether infants' looking differed as a function of which type of Familiarization they had experienced.

First we confirmed that infants in all experiments had the same amount of visual exposure to the objects during the Familiarization trials. For all three experiments, we measured how long infants looked during each of the 10 5-s Familiarization trials. A total of 15 infants from each experiment were included in this analysis; we were unable to code looking time during Familiarization trials for the remaining three infants due to a video recording error that spared the Test trials only. We then summed each infant's looking time across the 10 Familiarization trials and analyzed these in a one-way ANOVA with Experiment (1, 2a, or 2b) as a between-subjects factor. We found no differences in infants' total visual experience with the objects during Familiarization trials between Experiment 1 (mean = 29.46 s, SD = 5.04 s), Experiment 2a (mean = 31.15, SD = 7.41 s), and Experiment 2b (mean = 26.69 s, SD = 5.93 s) ($F_{2,42} = 1.97$, $p = 0.15$). As such, any difference in infants' Test trial performance across experiments could not be due to differences in infants' total visual experience with the objects.

Next we asked whether infants differed across the three experiments in their looking times during the Baseline trials. We conducted a repeated-measures ANOVA with Baseline Objects (4 objects or 3 objects) as a within-subjects factor and Experiments (1, 2a, or 2b) as a between-subjects factor. There was a significant main effect of Baseline objects ($F_{1,45} = 10.96$, $p = 0.002$, $\eta^2 = 0.20$), with infants looking significantly longer at four objects than at three. There was no Baseline Objects $\times$ Experiment interaction ($F_{2,45} = 0.30$, $p = 0.74$, $\eta^2 = 0.01$), suggesting that infants' pattern of looking during the Baseline trials did not differ across the three experiments.

Finally, we analyzed infants' Test trial performance using an omnibus repeated-measures ANOVA, with Test Outcome (Expected (4 objects) or Unexpected (3 objects)) and Trial Pair (1st, 2nd, or 3rd) as within subjects factors and Experiments (1, 2a, or 2b) as a between-subjects factor. This revealed a significant main effect of Test Outcome ($F_{1,45} = 4.02$, $p = 0.05$, $\eta^2 = 0.08$), which was moderated by a significant Test Outcome $\times$ Experiment interaction

($F_{2,45} = 3.65$, $p = 0.03$, $\eta^2 = 0.14$). We probed for the source of this predicted interaction with a series of planned repeated measures ANOVAs. Comparison of performance in Experiments 2a and 2b revealed no Test Outcome × Experiment interaction ($F_{1,30} = 0.06$, $p = 0.82$, $\eta^2 = 0.002$); infants looked longer at the Unexpected 3-object Test outcomes across both of these experiments. In contrast, comparison of performance in Experiments 1 and 2a revealed a significant Test Outcome × Experiment interaction ($F_{1,30} = 5.16$, $p = 0.03$, $\eta^2 = 0.15$), as did comparison of performance in Experiments 1 and 2b ($F_{1,30} = 5.85$, $p = 0.02$, $\eta^2 = 0.16$). Infants looked longer at Unexpected 3-object test outcomes than at Expected 4-object outcomes in Experiment 2a but not in Experiment 1, and in Experiment 2b but not in Experiment 1.

Returning to our omnibus analysis, we observed a significant main effect of Trial Pair ($F_{2,90} = 9.96$, $p < 0.001$, $\eta^2 = 0.18$), but no Trial Pair × Experiment interaction ($F_{4,90} = 0.82$, $p = 0.51$, $\eta^2 = 0.04$): infants looked longer overall on earlier trial pairs than later trial pairs regardless of which experiment they were in. We also found a significant main effect of Experiment ($F_{2,45} = 9.90$, $p < 0.001$, $\eta^2 = 0.31$), with pairwise comparisons showing infants looking longer overall in Experiment 2a than in Experiment 1 ($p = 0.003$) or Experiment 2b ($p < 0.001$), with no difference between overall looking in Experiments 1 and 2b ($p = 0.27$). There were no other significant effects (all $ps > 0.05$).

4.3. Discussion

Like infants in Experiment 2a, infants in Experiment 2b appeared to use the regularities available across the Familiarization trials to chunk representations of individual objects into higher order units, and thereby to remember the presence of four hidden objects during the Test trials. These infants observed fewer kinds of temporal regularities than infants in Experiment 2a, in that objects' spatial positions and order of placement within a pair were not perfectly reliable. Despite this, infants were able to use the reliable co-occurrence between objects of particular shapes and colors to form chunks. In this sense, experience with the objects' past histories changed infants' memory representations and enhanced infants' memory performance. Further, our results suggest that infants' chunked representations did not encode rigid spatial or temporal relationships between the components of the chunk, but instead were relatively flexible.

Our conclusion that infants chunked in Experiments 2a and 2b is supported by the elimination of a variety of alternative explanations. First, infants' Test trial performance in Experiments 2a and 2b could not have solely reflected long-term expectations of objects' spatial positions, because infants in Experiment 2b observed the objects within each pair occupying different positions across trials. Infants' performance also could not have been due to different amounts of exposure to the objects during Familiarization trials, as infants received the same amount of visual exposure to all of the objects across Experiments 1, 2a, and 2b. Nor could infants' performance have resulted from simply having been familiarized with pairs of objects prior to Test. Infants received equal exposure to pairs across the three experiments, yet they failed to remember four hidden objects in Experiment 1 and succeeded in Experiments 2a and 2b. Therefore, the results of Experiments 1, 2a, and 2b suggest that even when an array contains no immediately available snapshot cues, infants can use regularities that unfold over time to form more efficient, chunked representations of the array.

However, an outstanding question concerns the locus of the observed chunking effect. Infants' Familiarization experience in Experiments 2a and 2b apparently led them to represent the objects as chunks. There are at least two possible accounts of how these chunks affected their test performance. Infants in Experiments 2a and 2b may have used the chunking experience accumulated during Familiarization to parse the test arrays as also containing chunks. That is, upon seeing the four test objects on stage (before the objects were hidden behind the screen), infants may have created representations of two chunked pairs. These pairs may have been maintained in working memory while the objects were occluded, and then compared to the revealed 3-object and 4-object test outcomes. On this account, infants' longer looking at the unexpected 3-object array reflects a mismatch between the representation stored in working memory moments before the occlusion, and the array that was later revealed. Alternatively, infants conceivably could have ignored the hiding event altogether, and simply compared the 3-object and 4-object test arrays to longer-term memory representations of chunks formed during the Familiarization. On this account, longer looking at the 3-object array reflects a mismatch between the representation stored minutes before, during the Familiarization, and the array that was later revealed—with no object tracking implicated. Note that both of these accounts requires that infants formed higher-order, chunked representations during Familiarization.

To adjudicate between these accounts, we conducted an experiment in which no object tracking was required. In Experiment 3, infants saw Familiarization trials in which objects were paired with multiple regularities, just as in Experiment 2a. However, this time infants never saw any objects being hidden during the Test trials. Instead, they simply saw the occluder lifted to reveal either three or four objects, and their looking time was measured. If infants in Experiments 2a and 2b were responding on the basis of a mismatch between the objects tracked over occlusion and the objects that were revealed, then infants in Experiment 3 should show no preference between the two test outcomes, since they had no basis to form an expectation of what should be behind the occluder. If, however, infants in Experiments 2a and 2b were responding based on a longer-term memory representation of chunks formed during Familiarization (e.g., comparing the features seen in the chunks presented during Familiarization to the features seen in the chunks presented in the Test trials), then infants should look longer at the Unexpected 3-object outcome, just as in Experiment 2a.

5. Experiment 3: Multiple regularities, no hiding event

5.1. Methods

5.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months 23 days; range 11 months 25 days–13 months 13 days; 13 girls). Two additional infants participated but were excluded from analysis due to fussiness (1) or experimenter error (1).

5.1.2. Materials

Materials were identical to those in Experiments 1, 2a, and 2b.

5.1.3. Procedure

Baseline trials were identical to those in Experiments 1, 2a, and 2b. Familiarization trials were identical to those in Experiment 2a: infants saw the objects paired with multiple regularities (Fig. 1, middle panel).

Test trials proceeded similarly to Baseline trials. During each Test trial, the stage curtain was raised to reveal the occluding screen already sitting on the stage. The experimenter then lifted the screen to reveal either all four objects (4-object Outcome) or only three objects (3-object Outcome). Thus, unlike in Experiments 1, 2a, and 2b, infants did not see objects placed in front of and then hidden behind the occluding screen during Test trials.

As in Experiments 1, 2a, and 2b, a different object was chosen for omission from the array for each 3-object Outcome, counterbalanced across infants. 4-object and 3-object Outcomes alternated three times, resulting in six total Test trials. Trial order (4-object or 3-object Outcome first) was counterbalanced across participants.

Infants' looking duration was measured in real-time by an observer who could not see what infants were seeing. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high ($r = 0.96$).

5.2. Results

Analyses were conducted on log-scaled looking times. An analysis of infants' looking during the two Baseline trials revealed a slight but non-significant preference to look at the four-object array over the three-object array (paired samples $t_{15} = -0.55$, $p = 0.59$). We next analyzed infants' looking during the Test trials with a 2 (Test Outcome: 4 objects or 3 objects[3]) × 3 (Trial Pair: 1st, 2nd, or 3rd) repeated measures ANOVA; this revealed no main effect of Test Outcome ($F_{1,15} = 1.03$, $p = 0.32$, $\eta^2 = 0.06$), no main effect of Trial Pair ($F_{2,30} = 2.90$, $p = 0.07$, $\eta^2 = 0.16$), and no Test Outcome × Trial Pair interaction ($F_{2,30} = 1.76$, $p = 0.18$, $\eta^2 = 0.10$). Infants' looking times did not differ between 4- and 3-object outcomes.

Next we asked whether infants' pattern of looking to three-object versus four-object arrays differed between Baseline and Test trials. A 2 (Trial Type: Baseline or Test) × 2 (Outcome: 3 objects or 4 objects) repeated measures ANOVA revealed no main effect of Trial Type ($F_{1,15} = 1.55$, $p = 0.23$, $\eta^2 = 0.09$) or Outcome ($F_{1,15} = 0.89$, $p = 0.36$, $\eta^2 = 0.05$), and no interaction between Trial Type and Outcome ($F_{1,15} = 0.004$, $p = 0.94$, $\eta^2 < 0.001$). Infants looking did not differ between Baseline and Test trials (see Fig. 4).

Infants in Experiments 3 and 2a were shown the same temporal regularities during Familiarization, but unlike infants in Experiment 2a, infants in Experiment 3 did not look longer at 3-object versus 4-object outcomes during Test trials. We therefore confirmed that infants in Experiment 3 had the same amount of visual experience with the objects during Familiarization trials as infants in Experiments 2a. We summed infants' looking time across the 10 5-s Familiarization trials and found no difference in infants' total visual experience with the objects during Familiarization between Experiment 2a (mean = 31.15 s, SD = 7.41 s) and Experiment 3 (mean = 31.80 s, SD = 4.08 s) (one-way ANOVA $F_{1,29} = 0.09$, $p = 0.75$).

5.3. Discussion

After being familiarized to objects paired with multiple regularities, infants in Experiment 3 demonstrated no preference for the 3-object Test outcome versus the 4-object Test outcome. Combined with the successes observed in Experiment 2a (which contained identical Familiarization trials to those in Experiment 3) and Experiment 2b, this suggests that seeing a hiding event was crucial to infants' Test preferences.

Together, the results of Experiments 1–3 suggest that infants can use temporal regularities that unfold over time to chunk objects, and thereby increase memory. In order to chunk objects in this way, infants had to attend to objects' features during both the Familiarization and Test trials. During Familiarization, infants had to notice that the objects were featurally distinct from one another, and that there were reliable regularities between their features. Then, at Test, infants had to recognize the same features they had seen during Familiarization, and use these features to represent the four test objects as two chunks of two, rather than as four individuals.

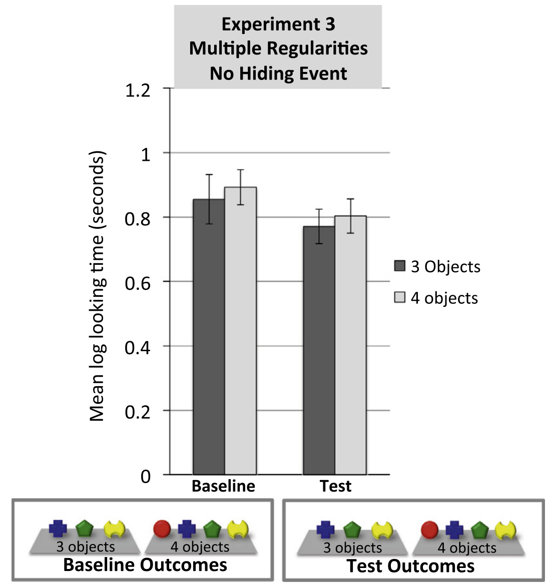

Fig. 4. Mean log looking times to the Baseline and Test trials in Experiment 3. Baseline and Test outcomes are shown in the bottom panels. Error bars show ±1 SEM.

These results raise a question about these new, chunked object representations: did these more efficient chunks actually contain information about the very features that were required for their formation? In the case of adults, the answer appears to be yes. In the experiments by Brady et al. (2009), adults remembered the colors of more items when the items' colors co-occurred with high likelihood across trials. Because the dependent measure of Brady and colleagues required memory for the items' features, the chunks formed by adults in response to the items' co-occurrence histories must have included featural information.

However, one reason to question whether infants, too, remember the features of chunked objects is a recent pattern of findings that infants sometimes represent objects' existence without remembering their specific features (Kibbe & Leslie, 2011; Rosenberg & Feigenson, submitted for publication), especially as the number of objects being maintained in memory increases (Kibbe & Leslie, 2013; Zosh & Feigenson, 2012). Because the Unexpected Test outcomes in our experiments always involved the complete disappearance of one of the four hidden objects, infants need not have maintained objects' features in memory in order to detect a violation. Infants may have used temporal regularities learned during Familiarization to chunk the four-object array into two sets of two objects, whose representations could be stored and maintained in working memory, yet failed to also store the features of the chunked object representations. Such a failure would lead infants to expect arrays of four objects, but to have no expectations about the objects' features.

To address this, in our last two experiments we asked whether infants who had the opportunity to use temporal regularities to form chunks not only remembered the existence of the chunked objects, but also the objects' features. We first familiarized infants with four objects, presented in pairs containing temporal regularities across trials as in Experiment 2a. At Test, infants then saw these four objects being hidden behind the occluding screen. This time, we probed infants' memory for the objects' features rather

[3] Unlike in Experiments 1, 2a, and 2b, here we refrain from labeling the Test outcomes *Expected* and *Unexpected* because there is no preceding hiding event from which infants could form an expectation about what is behind the screen.

than their existence by revealing either the very same objects that had just been hidden (i.e., disk, cross, pentagon, bowtie were hidden and disk, cross, pentagon, bowtie were revealed) or four objects, two of which had unexpectedly changed their features (e.g., disk, cross, pentagon, bowtie were hidden, and disk, disk, pentagon, pentagon were revealed). If infants successfully differentiated these two outcomes, it would suggest that they had stored the features of the objects in memory, either bound to individual object representations in working memory, or as unbound associations in long-term memory. If infants failed, it would suggest that they had stored representations of chunks in working memory (using temporal regularities to chunk arrays into two sets of two) but did not remember the objects' features.

Given that a null result in the above experimental design has potential theoretical value, and is predicted on some accounts of infants' object representations (e.g. Kibbe & Leslie, 2013), we wished to strengthen our ability to interpret a possible lack of looking preference across Test trials. Therefore, we first aimed to confirm that, under our testing conditions, infants could remember object features when the number of hidden objects fell within typical working memory limits (i.e., when no chunking was required). In Experiment 4 we familiarized infants with objects paired randomly (as in Experiment 1), then showed them Test trials in which just two objects with different features were hidden. We then compared infants' looking to outcomes in which those same two objects were revealed, with their looking to outcomes in which one of the objects was revealed to have unexpectedly changed its features. We predicted that infants would successfully detect the unexpected change in object features in these two-object arrays.

6. Experiment 4: Detecting an identity change in a two-object array

6.1. Methods

6.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months, 21 days, range 12 months, 0 days–13 months, 21 days; 8 girls). Nine additional infants participated but were excluded due to fussiness (5), parental interference (2), experimenter error (1), or uncorrected visual abnormality (1).

6.1.2. Materials

Materials were identical to those in Experiments 1, 2a, and 2b. In addition, four duplicate objects were used (another red disk, blue cross, green pentagon, and yellow bowtie).

6.1.3. Procedure

The Baseline trials proceeded as in Experiment 1. Even though the Test trials in Experiment 4 never contained all four objects, we showed infants all four objects during the Baseline trials in order to match infants' visual experience to that in Experiments 1, 2a, and 2b. But as the Baseline arrays and Test arrays were now no longer matched (i.e., infants in Experiment 4 saw Baseline arrays containing three versus four objects, but saw Test arrays containing just two objects), we did not compare infants' looking during Baseline trials with their looking in the later Test trials.

As in Experiment 1, infants next received a Familiarization to all four objects, presented in random pairs. The purpose of this Familiarization was again to equate infants' visual exposure to the objects with that in our previous experiments. Finally, on each Test trial, infants saw the experimenter place the occluding screen on the empty stage, and then place two objects in front of the screen. The identities of these objects were chosen to match the co-occurring pairs in Experiments 2a, 2b, and 3. Thus, one group of infants saw a disk and a cross on half of the Test trials and a pentagon and a bowtie on the other half, and another group of infants saw a bowtie and a disk on half of the Test trials and a cross and a pentagon on the other half. After 4 s during which the two objects remained visible, the experimenter hid both objects sequentially behind the screen. Finally, infants saw the screen lifted to reveal, on alternating Test trials, the same two objects just hidden (e.g., disk and cross; Expected Outcome), or a two object array in which one of the hidden objects had changed identity to match that of the other (e.g., disk and disk; Unexpected Outcome).

For the purpose of counterbalancing, infants saw eight total test trials, alternating between Expected and Unexpected Outcomes. Thus, infants saw two different pairs hidden four times each, with each object in the pair changing once (e.g., if disk and cross were hidden in an Unexpected Outcome trial, then infants saw one trial in which disk, disk was revealed and one trial in which cross, cross was revealed).

Infants' looking times were coded in real-time by an observer who could not see what infants were seeing. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high ($r = 0.96$).

6.2. Results

Analyses were conducted on log-scaled looking times. A repeated-measures ANOVA with Test Outcome (Expected or Unexpected) and Trial Pair (1st, 2nd, 3rd, or 4th) as within-subjects factors revealed a significant main effect of Test Outcome ($F_{1,15} = 36.39$, $p < 0.001$, $\eta^2 = 0.71$). Infants looked longer at the Unexpected Outcomes, in which the identity of one of the objects had changed, than at the Expected Outcomes (Fig. 5). There was no main effect of Trial Pair ($F_{3,45} = 1.40$, $p = 0.26$, $\eta^2 = 0.09$) and no Test Outcome × Trial Pair interaction ($F_{3,45} = 1.35$, $p = 0.27$, $\eta^2 = 0.08$).

7. Experiment 5: Detecting an identity change in a two-chunk array

Experiment 4 confirmed that, with our stimuli and testing conditions, infants remember the features of objects in a two-object array. In light of this positive result, we next asked whether infants would also detect such a feature change in arrays that had been chunked using temporal regularities among object features (as in Experiment 2a).

7.1. Methods

7.1.1. Participants

Sixteen healthy, full-term infants participated (mean age 12 months 29 days; range 12 months 15 days–13 months 22 days; 7 girls). Four additional infants participated but were excluded from analysis due to fussiness (1), parental interference (2), or experimenter error (1).

7.1.2. Materials

Materials were identical to those in Experiment 4.

7.1.3. Procedure

As in Experiments 1, 2a, and 2b, we used two Baseline trials to measure infants' initial interest in the object arrays that would later be shown in the Test trials. As such, both Baseline arrays contained four objects. The Mixed Identities array contained the same four unique objects that had been shown in the 4-Object Baseline trials of Experiments 1, 2a, and 2b (e.g., disk–cross–pentagon–bow

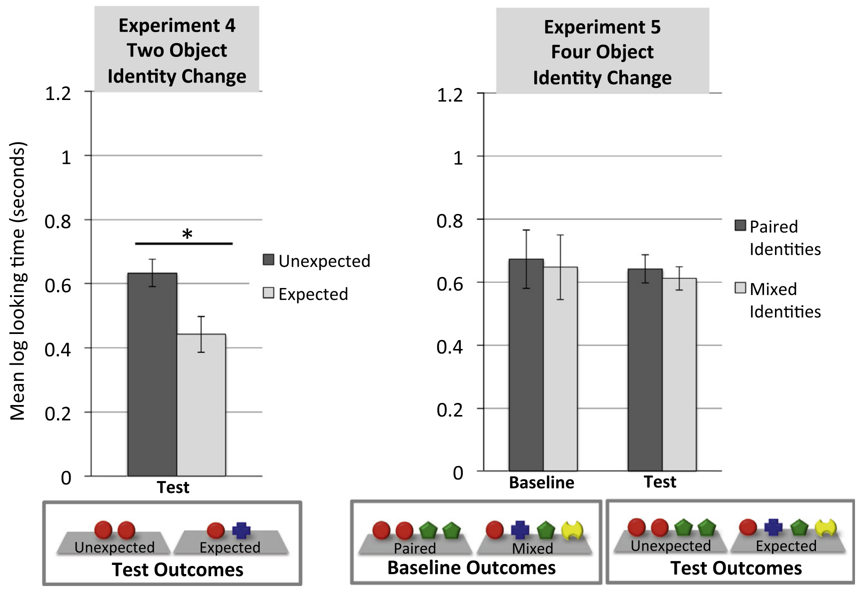

Fig. 5. Mean log looking time to the Test trials in Experiment 4, and to Baseline and Test trials in Experiment 5. Bottom panels show Test outcomes for Experiment 4 (left panel) and Baseline and Test outcomes for Experiment 5 (right panels). Error bars show ±1 SEM.

tie). The Paired Identities array contained two pairs of featurally identical objects (e.g., disk–disk–pentagon–pentagon). The objects in the Paired Identities array were chosen to match the first Unexpected Test outcome (see below).

The 10 Familiarization trials proceeded exactly as in Experiment 2a (Fig. 1, middle panel). Infants were given the opportunity to observe multiple sources of regularities among objects: there was 100% co-occurrence between object features, objects always maintained the same relative spatial positions within a pair, and objects were always placed in the same relative temporal order within a pair. As in Experiment 2a, infants were randomly assigned to see one of two yoked pairings: disk–cross, pentagon–bowtie or bowtie–disk, cross–pentagon.

The Test trials began like those in Experiments 1, 2a, and 2b. Infants saw the experimenter reach down and place the occluding screen on the empty stage, then saw her place the four unique objects in front of the screen one at a time. As in Experiments 2a and 2b, the order in which the objects were placed matched the object pairings used in the Familiarization trials (e.g., if infants had been familiarized with the pairs disk–cross, pentagon–bowtie, then the objects in the Test trial were presented in the order disk–cross–pentagon–bowtie). As in our previous experiments, infants saw the objects resting in front of the screen for 4 s, then saw them hidden one at a time behind the screen, starting from the left. Finally, the screen was lifted to reveal one of two outcomes (Fig. 2). In the Expected Outcome, the same four objects that had just been hidden were now revealed (this was identical to the Expected Outcome in Experiments 1, 2a, and 2b and to the Mixed Identities Baseline trial). In the Unexpected Outcome, one object in each pair was revealed to have changed identity, such that two pairs of featurally identical objects were revealed (as in the Paired Identities Baseline trial). For example, if infants had seen disk–cross–pentagon–bowtie hidden, they might then see cross–cross–pentagon–pentagon revealed. Infants saw three Expected and three Unexpected trials in alternation, for a total of six Test trials. On each of the three Unexpected trials, different objects were chosen to change identities: either the first object in each pair (e.g., infants saw disk–cross–pentagon–bowtie hidden, and saw cross–cross–bowtie–bowtie revealed), the second object in each pair (e.g., infants saw disk–cross–pentagon–bowtie hidden, and saw disk–disk–pentagon–pentagon revealed), or the first object from one pair and the second object from the other pair (e.g., infants saw disk–cross–pentagon–bowtie hidden, and saw cross–cross–pentagon–pentagon revealed).

Infants' looking times were coded in real-time by an observer who could not see what infants were seeing. Two additional observers later recoded infants' looking times frame-by-frame offline using Preferential Looking Coder 1.3.3 (Libertus, 2011). Inter-observer agreement was high ($r = 0.99$).

7.2. Results

Analyses were conducted on log-scaled looking times. We first examined infants' looking during the two Baseline trials. We found that infants had no significant preference to look at the Mixed Identities array, which contained four unique objects, versus the Paired Identities array, which contained two pairs of identical objects (paired samples $t_{15} = 0.24$, $p = 0.82$, two-tailed). Next we analyzed infants' looking during the critical Test trials with a 2 (Test Outcome: Expected (Mixed Identities) or Unexpected (Paired Identities)) × 3 (Trial Pair: 1st, 2nd, or 3rd) repeated measures ANOVA. This revealed no main effect of Test Outcome ($F_{1,15} = 0.37$, $p = 0.55$, $\eta^2 = 0.02$); infants did not look longer when two of the four hidden objects changed identities during occlusion than when all four expected objects were revealed. There also was no main effect of Trial Pair ($F_{2,30} = 0.13$, $p = 0.88$, $\eta^2 = 0.008$) and no Test Outcome × Trial Pair interaction ($F_{2,30} = 1.75$, $p = 0.19$, $\eta^2 = 0.11$).

As in Experiments 1, 2a, and 2b, we then asked whether infants' looking patterns differed between Baseline and Test trials. A 2 (Trial Type: Baseline or Test) × 2 (Outcome: Paired Identities or Mixed Identities) repeated measures ANOVA revealed no main effect of either Trial Type ($F_{1,15} = 0.16$ $p = 0.69$, $\eta^2 = 0.01$) or Outcome ($F_{1,15} = 0.20$, $p = 0.66$, $\eta^2 = 0.01$), and no significant interaction between Trial Type and Outcome ($F_{1,15} < 0.01$, $p = 0.97$, $\eta^2 < 0.01$). Infants' pattern of looking did not change significantly between Baseline and Test trials (Fig. 5).

Infants in Experiment 5 observed the same co-occurrence regularities during Familiarization as infants in Experiment 2a, but failed to look longer at the unexpected identity change outcome, whereas infants in Experiment 2a looked longer at the numerical change outcome. We considered one possible source for this difference by asking whether infants in Experiments 5 and 2a differed in their total visual experience with the objects prior to the Test trials. We measured infants' looking times during each of the 10 5-s Familiarization trials in Experiment 5 and compared these to infants' looking during the 10 Familiarization trials of Experiment 2a. We found no significant difference in the amount of time infants looked at the objects during the Familiarization trials of Experiment 5 (mean = 29.03, SD = 8.58 s) versus Experiment 2a (mean = 31.15 s, SD = 7.41 s) (t_{29} = 0.70, p = 0.50, two-tailed).

7.3. Discussion

Although infants in Experiments 2a and 2b successfully used co-occurrences among object features to chunk and thereby remember the existence of four hidden objects, infants in Experiment 5 showed no evidence of maintaining these very features in their stored representations. This is surprising, given that infants must have encoded and represented objects' features from both the Familiarization and the Test arrays. Seeing co-occurrences between features during Familiarization was required for infants to remember the presence of four hidden objects at Test (as shown by infants' success in Experiments 2a and 2b and failure in Experiment 1); hence these features must have entered into infants' representations. Yet the results of Experiment 5 suggest that these features apparently were not retained in infants' memory of the Test array, or were not accessed when comparing the remembered Test array to the observed Test array. Although we remain cautious in interpreting this null result, infants' failure to respond to unexpected changes in objects' features is consistent with previous work in which infants sometimes appear to store representations of objects without maintaining or using representations of the objects' features (Kibbe & Leslie, 2011; Kibbe & Leslie, 2013; Rosenberg & Feigenson, submitted for publication; Zosh & Feigenson, 2012). It is also consistent with working memory research showing that adults can maintain object representations while forgetting particular features of those objects (Brady, Konkle, Alvarez, & Oliva, 2013), and that as the number of remembered objects increases, adults maintain the specific identities of fewer objects and make more errors in binding object identities to object locations (Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; Saiki, 2003).

Importantly, the finding that infants failed to detect changes to the identities of the hidden objects in Experiment 5 provides additional evidence against an alternative account of infants' performance in Experiments 2a and 2b. Infants in these experiments could not have been simply comparing the observed Test arrays to long-term memory associations between objects' features, without representing the Familiarization and Test arrays as containing object chunks. If they had been relying on long-term memories of associations between features, infants would have differentiated Test arrays in which features were associated in the same ways as they had been during Familiarization (Expected Outcomes) from arrays in which the features were differently associated or when some associated features were now absent (Unexpected Outcomes). Our finding that infants did not in fact differentiate these arrays suggests that infants were not responding on the basis of remembered featural associations, but rather on the basis of persisting representations of object chunks.

8. General discussion

Previous research has shown that when perceptual grouping cues are available, infants can use these cues to expand object memory by chunking. In these previous studies, infants made use of cues liked shared features or spatial proximity that were available in a single glance (Feigenson & Halberda, 2004; Feigenson & Halberda, 2008; Rosenberg & Feigenson, 2013). In the present series of experiments, we asked whether infants also can chunk using cues that are only observable over time—that is, whether infants can learn temporal regularities between the features of particular objects, and then use these regularities to chunk object representations in memory, in the absence of any snapshot chunking cues.

First, in Experiment 1 we confirmed that infants fail to remember the existence of four unique objects in the absence of any regularities that could be used to support chunking. When first familiarized with four objects presented in successive random pairs, and then tested with all four objects hidden in a single location, infants failed to differentiate the expected 4-object outcome from the unexpected 3-object outcome. That is, infants exhibited the limit on working memory capacity that is typical of infants of this age (e.g., Feigenson & Carey, 2003; Feigenson & Carey, 2005). Next, in Experiment 2a, we introduced multiple sources of temporal regularities between objects during the familiarization. Across trials, objects of particular shapes and colors reliably co-occurred, always appeared in the same relative spatial positions, and always appeared in the same relative temporal order. This time we found that infants successfully remembered the existence of the four hidden objects. In Experiment 2b, we replicated and extended this result by reducing the number of temporal regularities available during the familiarization trials. Although object identities were again paired with reliable co-occurrence throughout the familiarization, the objects' relative spatial location and order of placement varied. Still we found that infants successfully remembered the existence of all four hidden objects. In Experiment 3, we showed that infants' Test preferences required having seen objects hidden immediately before the Test arrays were revealed. When infants were familiarized to objects appearing in regular pairs (as in Experiment 2a) and then shown the test arrays with no preceding hiding event, infants exhibited no looking preferences. Together, the results from our first four experiments suggest that infants can learn associations between object features within a few minutes' time, and then use this information to more effectively track an array of hidden objects. Representing the objects in terms of two chunks of two, rather than in terms of four separate individuals, appeared to aid infants' memory.

However, our last two experiments revealed a striking limit to infants' chunking abilities. In these experiments we asked whether chunking using temporal regularities among object features not only allows infants to remember the existence of hidden objects, but also to remember the chunked objects' features. Surprisingly, we found that infants familiarized with temporal regularities and then shown four different objects being hidden failed to respond when half of the revealed objects had changed identity (Experiment 5). Yet infants did detect such an identity change when faced with a two-object array that did not require chunking (Experiment 4). Thus, at least under the conditions explored here, chunking via learned temporal regularities enhanced infants' memory for objects' existence but not memory for objects' features. Such a benefit might indicate that objects' features can be used to initially create chunks, but then are forgotten or discarded, leaving only representations of objects' existence (as in the "object-file" representations proposed by Kahneman, Treisman, and Gibbs (1992)). These bare object representations, despite containing little or no information about objects' features, would still support some comparisons between remembered and observed arrays, including comparisons of one-to-one correspondence.

Our results highlight both similarities and differences between the memory computations of infants and adults. Both populations are constrained in the number of items they can maintain in working memory. Both populations can use chunking to overcome this constraint. And both populations can leverage temporal regularities across events to support chunking (see also Stahl & Feigenson, 2014). However, our results suggest that infants may be more limited than adults in the extent to which such regularities aid memory. Adults appear to remember the features of objects that were chunked using temporal regularities (Brady et al., 2009). In contrast, infants in our task (and in a different chunking task by Rosenberg and Feigenson (submitted for publication)) showed no evidence of remembering the features of object chunks. Further work is needed in order to better understand this apparent difference between infant and adult performance (see Kibbe, in press). More work also remains in order to understand the mechanisms by which observers can chunk using temporal regularities. For example, infants in our experiments had many repeated exposures to the co-occurrences among object features. But it is unknown exactly how much experience with objects' past histories was required to support successful chunking. Adults in the studies by Brady et al. (2009) successfully chunked even though they saw features that co-occurred with only about 80% reliability. How reliable do the regularities have to be for infants to take advantage of co-occurrence information? These are questions that we hope will guide future research.

9. Conclusion

In summary, we found that 13-month old infants can use regularities that unfold over time to improve their memory for hidden objects. Infants rapidly learned associations between object features, and appeared to use these associations to chunk items in memory; this chunking increased the total number of objects infants remembered. However, although infants' sensitivity to the dynamics of object co-occurrences appeared to increase their ability to remember hidden objects' existence, it did not appear to help them remember the hidden objects' features. These results inform our understanding of both the flexibility and the limitations of early memory computations.

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