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Array heterogeneity prevents catastrophic forgetting in infants

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ABSTRACT

Working memory is limited in adults and infants. But unlike adults, infants whose working memory capacity is exceeded often fail in a particularly striking way: they do not represent *any* of the presented objects, rather than simply remembering as many objects as they can and ignoring anything further (Feigenson & Carey, 2003, 2005). Here we explored the nature of this "catastrophic forgetting," asking whether stimuli themselves modulate the way in which infants' memory fails. We showed 13-month old infants object arrays that either were within or that exceeded working memory capacity—but, unlike previous experiments, presented objects with contrasting features. Although previous studies have repeatedly documented infants' failure to represent four identical hidden objects, in Experiments 1 and 2 we found that infants who saw four contrasting objects hidden, and then retrieved just two of the four, successfully continued searching for the missing objects. Perceptual contrast between objects sufficed to drive this success; infants succeeded regardless of whether the different objects were contrastively labeled, and regardless of whether the objects were semantically familiar or completely novel. In Experiment 3 we explored the nature of this surprising success, asking whether array heterogeneity actually expanded infants' working memory capacity or rather prevented catastrophic forgetting. We found that infants successfully continued searching after seeing four contrasting objects hidden and retrieving two of them, but not after retrieving three of them. This suggests that, like adults, infants were able to remember up to, but not beyond, the limits of their working memory capacity when representing heterogeneous arrays.

1. Introduction

A hallmark of working memory is its limited capacity. When remembering briefly presented visual arrays, adults appear to store information from about only three or four individual items at once (e.g., Alvarez & Cavanagh, 2004; Broadbent, 1975; Cowan, 2001; Fukuda, Awh, & Vogel, 2010; Halberda, Sires, & Feigenson, 2006; Luck & Vogel, 1997; Song & Jiang, 2006; Sperling, 1960; Todd & Marois, 2004; Xu & Chun, 2006). For example, Luck and Vogel (1997) presented adults with visual arrays containing objects with different features. When a second array appeared moments later, adults successfully detected a change to the features of any of the objects when the initial array contained one, two, three, or four objects. But this ability declined precipitously when the arrays contained larger numbers. Similar limits have been observed for lists of verbal items being maintained for longer durations of several seconds; when chunking and rehearsal strategies are prevented, adults can recall only about three or four auditory items (for review, see Cowan, 2001).

This limited-capacity signature of working memory is also seen early in development. Some studies that tested memory for object features using tasks similar to those

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used with adults found that children's working memory capacity appears to increase over the early school years (Cowan, Johnson, & Saults, 2005; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Gathercole, 1999; Pailian, Libertus, Feigenson, & Halberda, submitted for publication; Riggs, McTaggart, Simpson, & Freeman, 2006; Riggs, Simpson, & Potts, 2011; Simmering, 2012), or even over infancy (Káldy & Leslie, 2005; Kwon, Luck, & Oakes, 2014; Rose, Feldman, & Jankowski, 2001; Ross-Sheehy, Oakes, & Luck, 2003), arriving at an asymptote of about three or four items. Other studies that measured memory for objects' existence, without requiring memory for particular features, found that much younger children demonstrate a working memory limit that is already similar to that of adults. In one series of experiments, infants ranging from 12- to 20-months old saw different numbers of identical objects hidden inside a box. Infants were allowed to retrieve either all of the objects or just a subset (with the other(s) surreptitiously removed by the experimenter). When only a subset of the hidden objects had been retrieved, infants successfully continued searching for the missing object(s) when the starting array contained two or three objects, but not when it contained four, six, or eight objects (Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003; Feigenson & Halberda, 2008; Rosenberg & Feigenson, 2013; see also Starkey, 1992). This working memory capacity limit also has been observed in infants who were offered a choice between two quantities of edible items hidden in containers. Infants successfully chose the greater quantity when each container held three or fewer objects (i.e., with choices of one vs. two and two vs. three crackers), but failed with larger numbers (i.e., with choices of two vs. four, three vs. four, and three vs. six crackers) (Feigenson, Carey, & Hauser, 2002; vanMarle, 2013). Finally, 9- to 12-month old infants have been shown to dishabituate to changes in visual arrays displaying one, two, or three items (either individual objects or collections of visual items) but not to changes in arrays containing four or more items (Strauss & Curtis, 1981; Zosh, Halberda, & Feigenson, 2011). Thus, research on children's memory has used a variety of paradigms (some testing memory for objects' features, and others testing memory for objects' existence), and retention durations (ranging from less than a second to several seconds). Although these studies differ in whether they find evidence of developmental increases in capacity, as well as in whether there is an opportunity for other memory systems to interact with working memory, they concur in finding that working memory in infants and children typically shows an upper limit of around three or four items. This limit is similar to that seen in studies of adults' visual and verbal working memory when strategies for rehearsal or chunking are prevented.

However, young children's working memory appears to diverge from that of adults in at least one striking way: the nature of the failure when capacity is exceeded. When faced with supra-capacity arrays containing more items than working memory can maintain, adults appear to represent three or four of the items and forget or fail to encode the rest. This is reflected by the smooth decline in their memory performance as the number of presented items exceeds capacity (Eng, Chen, & Jiang, 2005; Luck & Vogel, 1997; Song & Jiang, 2006; Vogel & Machizawa, 2004). For example, when shown arrays containing six objects, adults' detection of a change to any one of the objects was still above chance (Luck & Vogel, 1997), indicating that adults represented a subset of the array, with the likelihood of one of the remembered items being probed decreasing smoothly as array size increased. A similar pattern of remembering subsets of supra-capacity arrays is observed for verbal stimuli (e.g., Saults & Cowan, 2007; Unsworth & Engle, 2006), and in studies of neural activity: the inferior intra-parietal sulcus shows increasing activation for visual arrays containing one, two, three, or four objects, and asymptotic activation for larger arrays (Todd & Marois, 2004; Vogel & Machizawa, 2004; Xu & Chun, 2006).

In contrast, showing infants arrays that exceed their working memory capacity often impairs performance more dramatically. Take the task in which infants saw objects hidden in a box, saw a subset of these retrieved, and then were allowed to search the box. Twelve- to 14-month old infants who saw four objects hidden and just two of these retrieved failed to search for the remaining objects, offering no evidence that they remembered anything else having been hidden (Feigenson & Carey, 2003). Note that even if the 4-object array exceeded infants' working memory capacity, representing just three out of the four objects (as adults appear to do) would have led to successful continuation of searching. Furthermore, infants also failed to keep searching after four hidden objects had been hidden and just *one* object was retrieved (Feigenson & Carey, 2005)—a failure that persists until at least 20 months of age (Barner et al., 2007). Apparently, infants' representation of the contents of the box when four objects had been hidden either was entirely absent, or was so impoverished that a representation of four could not be discriminated from a representation of just a single object. The same striking failure emerges from the studies in which infants chose between two hidden quantities. Although infants reliably chose the greater quantity with choices of one vs. two and two vs. three crackers, they chose randomly with choices of two vs. four, three vs. six, one vs. four, and two vs. eight crackers (Feigenson & Carey, 2005; Feigenson et al., 2002; vanMarle, 2013). And in tasks measuring infants' ability to detect a featural change in a briefly presented array, infants of 6 months and younger, who successfully detected a change in a one-object array, failed to detect a change in arrays containing more than one (Kwon et al., 2014; Ross-Sheehy et al., 2003), even when every object in the array had changed its features (Oakes, Messenger, Ross-Sheehy, & Luck, 2009b; Oakes, Ross-Sheehy, & Luck, 2006). This suggests that when the number of visual items exceeded capacity, these infants did not remember the features of any of the items shown.

Infants' catastrophic memory failures when presented with supra-capacity arrays shows that, unlike adults, infants often do not remember just a subset of an array and ignore the remainder. These surprising failures start to shed light on the nature of infants' representations of supra-capacity arrays. Infants appear unable to represent an array of four objects as simply "more than one," as even this would have led to successful performance when infants saw four objects hidden and just one object retrieved, or when infants chose between four crackers and one cracker. Yet although infants failed to represent a four-object array as "exactly four," "approximately four," or even "more than one," they apparently formed *some* representation of a four-object array. When given a choice between a container holding four sequentially hidden crackers and a container holding no crackers (over which an empty hand was waved four times, to equate presentation activity), infants reliably chose the container with four. And when offered a choice between a single small cracker and four sequentially hidden large crackers, infants again reliably chose the container with four (Feigenson & Carey, 2005). Hence infants presented with supra-capacity arrays did remember that something had been presented, and also remembered at least some of the features of the presented objects (e.g., that the crackers in a particular location were large, rather than small). But they apparently did not maintain a representation of the number of items in the array, even in an implicit or coarse way (e.g., by distinguishing between singular and plural arrays).

Although infants' catastrophic forgetting has been observed in multiple studies using different paradigms, we know little about why infants experience this striking failure and why their performance differs from that of adults. In the present experiments we explored one factor that might contribute to catastrophic forgetting: array heterogeneity. Studies of adults' visual and verbal working memory have typically measured memory for contrasting items—for example, visual objects whose features differ (e.g., Alvarez & Cavanagh, 2004; Broadbent, 1975; Luck & Vogel, 1997; Song & Jiang, 2006; Sperling, 1960; Todd & Marois, 2004; Xu & Chun, 2006), or auditory items whose acoustical and semantic properties differ (e.g., Baddeley, Thomson, & Buchanan, 1975; Saults & Cowan, 2007). In contrast, many of the studies demonstrating catastrophic forgetting in infants used arrays of identical objects, and tested infants' memory for the objects' existence rather than for their features. Might infants' catastrophic forgetting be due, in part, to being presented with homogeneous arrays of identical items?

A modest amount of evidence suggests that array heterogeneity can affect infants' representations of arrays containing numbers of objects within working memory capacity. When habituated to two objects that contrasted in color, pattern, and texture, 7-month old infants responded to a change in the number of objects present. But when habituated to two identical objects, infants failed to respond to a change in object number and instead responded to a change in the objects' combined surface area (Feigenson, 2005). In another study, 4-month old infants were shown to better remember an object that was presented with another, different object, than when the same object was seen alone, suggesting that contrast between object features can aid infants' memory (Oakes, Kovack-Lesh, & Horst, 2009a). In addition, infants are less likely to make perseverative errors in an A not B task when the A and B objects contrast featurally (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001), and are more likely to form exclusive categories when presented with pairs of contrasting objects than pairs of identical objects (Kovack-Lesh & Oakes, 2007). Many current theories of memory hold that similarity between remembered items can lead to inter-item interference, resulting in impaired memory performance relative to conditions in which items have fewer shared features (e.g., Bunting, 2006; Endress & Potter, 2014). Such interference effects offer one explanation for the benefit of item heterogeneity on memory performance—an issue that we return to later.

In the present work we asked the following: given that object heterogeneity can influence infants' memory for within-capacity arrays, does heterogeneity also influence memory for supra-capacity arrays? In particular, do infants show the same catastrophic memory failure with heterogeneous arrays of contrasting objects as they have in previous studies using identical objects?

Objects can contrast with one another in many ways, including in their visual features (e.g., red ball vs. blue ball), category membership (e.g., ball vs. orange), and verbal labels (e.g., "ball" vs. "orange"). Previous research shows that infants are sensitive to all of these contrasts when deciding when to reach for hidden objects (e.g., Feigenson & Halberda, 2004, 2008; Xu, Cote, & Baker, 2005). Here we asked whether each of these sources of contrast would affect infants' memory for supra-capacity object arrays. In Experiment 1 we measured the effects of visual and verbal array heterogeneity by presenting infants with within-capacity and supra-capacity arrays of contrasting objects that either were labeled with familiar contrasting labels, or were labeled identically. In Experiment 2 we explored the effect of conceptual vs. perceptual array heterogeneity by presenting infants with contrasting objects that either were from known categories, or were novel. To preview our results, Experiments 1 and 2 demonstrated that infants benefitted significantly from array heterogeneity, successfully remembering arrays of four objects (in the face of previously observed failures), regardless of whether the objects were contrastively labeled or were from known object categories. Finally, in Experiment 3 we asked whether array heterogeneity actually *expanded* infants' working memory capacity, or rather helped infants successfully remember a subset of the objects in supra-capacity arrays (i.e., prevented catastrophic forgetting). Our results suggest that array heterogeneity allowed infants to perform in a more adult-like manner: infants remembered up to the limit of their working memory capacity, and ignored or forgot any further items.

2. Experiment 1

Previous experiments using the manual search procedure showed that infants remember one, two, and three hidden objects, but not four (Feigenson & Carey, 2003, 2005). That is, after seeing four objects hidden and only one or two of these objects retrieved, infants failed to keep searching for the missing objects. The arrays in these previous experiments always contained identical objects, and infants always heard identical verbal utterances (e.g., the experimenter pointed to each object prior to hiding it and said, "Look at this.").

Here we used the same procedure as these previous studies, but presented infants with heterogeneous rather than homogeneous arrays. Infants in Experiment 1 always saw objects that contrasted on the basis of multiple visual features. In addition, we manipulated the linguistic information available to infants. In one test block infants saw objects that their parents reported they knew the names of, and they also heard these objects labeled by the experimenter before the objects were hidden (Labeled Objects block). In the other test block infants saw objects that their parents reported they did not know the names of, and did not hear the objects labeled (Unlabeled Objects block).

Following the design of previous investigations (Barner et al., 2007; Feigenson & Carey, 2003, 2005), in one test block we measured infants' memory for arrays that contained numbers of objects expected to be within working memory capacity. In the other block we measured memory for arrays containing numbers of objects expected to exceed capacity. We predicted that if heterogeneity improves infants' working memory performance overall, then infants should show successful search patterns for both within-capacity and supra-capacity arrays regardless of labeling. If array heterogeneity does not improve infants' memory performance, then infants should show successful search patterns only for within-capacity arrays (as in previous studies), regardless of labeling. And if array heterogeneity improves infants' memory performance only when infants know and/or hear verbal labels for contrasting objects, then infants should succeed with all within-capacity arrays, but should succeed with supra-capacity arrays in the Labeled Objects block and fail in the Unlabeled Objects block.

2.1. Method

2.1.1. Participants

Thirty-two healthy, full-term infants participated (13 females; range = 12 months, 1 day to 13 months, 15 days; mean = 12 months, 27 days). Data from eight additional infants were excluded from analysis (for not knowing any words that could be used in the Labeled Objects block [2]; for fussiness [2]; for failure to produce the dependent measure on any trial [1]; for experimenter error [1]; for technical error [1], or for having more than two reaches greater than 2.5 SD from the mean [1]). Most infants were Caucasian and from middle- to upper-middle income households.

2.1.2. Materials

Infants retrieved objects from inside a black foam-core box (31.5 × 25 × 12.5 cm). The box had a spandex-covered opening in its front face (14 × 7.5 cm) with a slit through which infants could reach but not see. The box also had a concealed opening in the back through which the experimenter could surreptitiously reach to withhold objects on critical trials.

Small plastic toys served as stimuli (approximately 4.5 × 7 cm). We chose the toys on the basis of our estimation that about half of the infants in our sample would already know their verbal labels (based on published vocabulary norms reporting that about 50% of 12- to 15-month-old infants show comprehension of these objects' labels; Fenson et al., 1994). The objects were: ball, bottle, brush, bug, bus, car, cat, cow, doll, duck, elephant, fork, goat, phone, pig, rooster, shoe, spoon, and teddy bear. Which objects each infant saw and on which test block these were presented was determined by parental report of infants' linguistic knowledge. Before the experiment, parents completed a checklist inventory to indicate which of the objects' labels their child understood. The experimenter used this checklist to randomly select a set of stimulus objects for which each individual infant was reported to know the labels (to be used in the Labeled Objects block), and another set for which the infant did not (to be used in the Unlabeled Objects block). The objects in our inventory were used roughly equally often in both conditions, as which labels infants comprehended varied idiosyncratically.

2.2. Design and procedure

We used a modified 2 × 2 design. Each infant was tested in one block containing object arrays that were expected to be within working memory capacity, and another block containing arrays that were expected to exceed capacity. Each infant also was tested in a Labeled Objects block and an Unlabeled Objects block. For half of the infants, the within-capacity arrays (1 vs. 2 Objects) were Labeled and the supra-capacity arrays (2 vs. 4 Objects) were Unlabeled. The other infants saw the reverse: the within-capacity arrays (1 vs. 2 Objects) were Unlabeled and the supra-capacity arrays (2 vs. 4 Objects) were Labeled. As such, each infant contributed data to two of the four cells in the 2 × 2 design (as in previous studies using the manual search method; e.g., Feigenson & Halberda, 2008; Stahl & Feigenson, 2014). We did not use a design in which each infant contributed data to all four cells because our previous work suggested that the number of required trials would exceed the limits of infants' attention and willingness to engage in our task. Our design was not intended to reveal whether each individual infant would show effects of both labeling and array size, but rather to reveal whether, across the test population as a whole, any such effects were observed.

2.2.1. Familiarization

Infants sat in a highchair in front of a low table. The experimenter knelt to the infants' left and the parent sat approximately 0.6 m behind. A video camera recorded each testing session. The experimenter began by presenting infants with the empty box and demonstrating how objects could be hidden inside and then retrieved. The experimenter brought out a ring of plastic keys, showed it to infants, and inserted it through the opening in the front of the box. Infants were encouraged to reach in and retrieve the keys. Once infants had successfully reached in and retrieved the keys twice, familiarization was considered complete and the test phase began.

2.2.2. 1 vs. 2 Objects block

All infants were tested in a 1 vs. 2 Objects block (Fig. 1); for half of the infants this was the Labeled Objects block and for the other half of infants it was the Unlabeled Objects block. The presented objects were chosen randomly by the experimenter from the set for which parents reported their child knew the words (Labeled Objects block), or did not know the words (Unlabeled Objects block). The block contained three different measurement periods:

1-Object (None Remaining) measurement periods indexed infants' ability to maintain a single object representation in memory. The experimenter placed one object on top of the box, pointed to it, and either labeled it (Labeled Objects block) or did not label it (Unlabeled Objects block). In the Labeled Objects block she pointed and said, "Look! A (duck)! See? A (duck)!" In the Unlabeled Objects block she pointed and said, "Look at that! See that?" She then picked up the object and, after making sure infants were watching, inserted it through the opening in the front of the box. Infants were allowed to reach into the box and retrieve the object, after which the experimenter took the object away and placed it out of view beneath the table.[1] A 10-s measurement period followed in which the amount of time infants spent searching the box was measured. During this measurement period the experimenter looked down so to not provide infants with any cues. After 10 s, the experimenter looked up and said, "Good job!" and removed the box from the table.

2-Objects (More Remaining) measurement periods indexed infants' ability to maintain two object representations in memory concurrently. The experimenter placed two different objects on top of the box in a single hand motion, then pointed to each and either labeled each object twice (Labeled Objects block) or did not label them (Unlabeled Objects block). In the Labeled Objects block she pointed and said, "Look! A (duck)! See? A (duck)! Look! A (car)! See? A (car)!" In the Unlabeled Objects block she pointed and said, "Look at that! See that? Look at that! See that?" The experimenter then picked up both objects in one hand (to equate the amount of motion with that in the 1-Object presentation) and inserted them into the box. As she did this, she used her other hand to secretly reach through the opening in the back of the box, grasp one of the inserted objects, and hold it out of infants' reach. Infants were allowed to reach in through the front of the box and retrieve the remaining object. As soon as infants had retrieved the object, the experimenter took it away and put it out of sight under the table, and the 10-s measurement period began. Throughout these 10 s the experimenter continued to secretly hold the remaining object out of reach in the back of the box. After 10 s, the experimenter said, "Can I help you find something?" She reached in with her free hand and pulled the previously withheld object out of the front of the box. She showed the object to infants, then placed it out of sight under the table.

A final measurement period then began (2-Objects, None Remaining). This last measurement period served as a check that when multiple objects had been hidden, infants did not continue searching the box indiscriminately regardless of the number of objects that had already been retrieved (for example, because seeing heterogeneous objects increased infants' general motivation to search the box, no matter how many objects were expected inside).

In the 1 vs. 2 Objects block, accurate memory for the hidden arrays would be revealed by a pattern of little searching on the 1-Object (None Remaining) measurement period, increased searching on the 2-Objects (More Remaining) period, and little searching again on the 2-Objects (None Remaining) period.

Whether infants first were tested in a 1-Object (None Remaining) or a 2-Objects (More Remaining) measurement period was counterbalanced across infants. The 2-Objects (None Remaining) measurement period always followed the 2-Objects (More Remaining) measurement period. Each infant was tested twice with these three measurement periods, and each infant saw the same two objects used throughout the entire 1 vs. 2 block. One object was randomly chosen for use in the first 1-Object (None Remaining) trial; this same object was the first object retrieved in the first 2-Object (More Remaining) trial. The other object was used in the second 1-Object (None Remaining) trial, and was the first object retrieved in the second 2-Object (More Remaining) trial. This prevented any object-specific effects (such as a strong preference for a particular object) from biasing infants' searching.

2.2.3. 2 vs. 4 Objects block

All infants also were tested in a 2 vs. 4 Objects block (Fig. 2); for half of the infants this was the Labeled Objects block and for the other half it was the Unlabeled Objects block. The presented objects were chosen randomly from the set for which parents reported their child knew the words (Labeled Objects block), or did not know the words (Unlabeled Objects block). This block contained three measurement periods:

2-Objects (None Remaining) measurement periods indexed infants' ability to maintain two object representations in memory concurrently. The experimenter placed two different objects on top of the box, pointed to them, and either labeled the objects twice (Labeled Objects block) or did not label them (Unlabeled Objects block). In the Labeled Objects block she pointed and said, "Look! A (bottle)! See? A (bottle)! Look! A (pig)! See? A (pig)!" In the Unlabeled Objects block she pointed and said, "Look at that! See that? Look at that! See that?" She then picked up the objects and inserted them into the box, using separate hand movements for each object. Infants were allowed to reach into the box and retrieve both objects, with the experimenter assisting if infants did not immediately do so. Then the experimenter quickly took both objects away and placed them out of sight beneath the table, and a 10 s measurement period followed. After 10 s, the experimenter said, "Good job!" and removed the box from the table.

4-Objects (More Remaining) measurement periods indexed infants' ability to maintain four object representations in memory concurrently. The experimenter placed four different objects on top of the box using two hand motions (i.e., placed the objects two at a time), then

[1] If infants did not immediately retrieve the object (which happened rarely), the experimenter assisted. This was done across all trials in all experiments, so that the retention interval between object hiding and object retrieval was equated across all measurement periods.

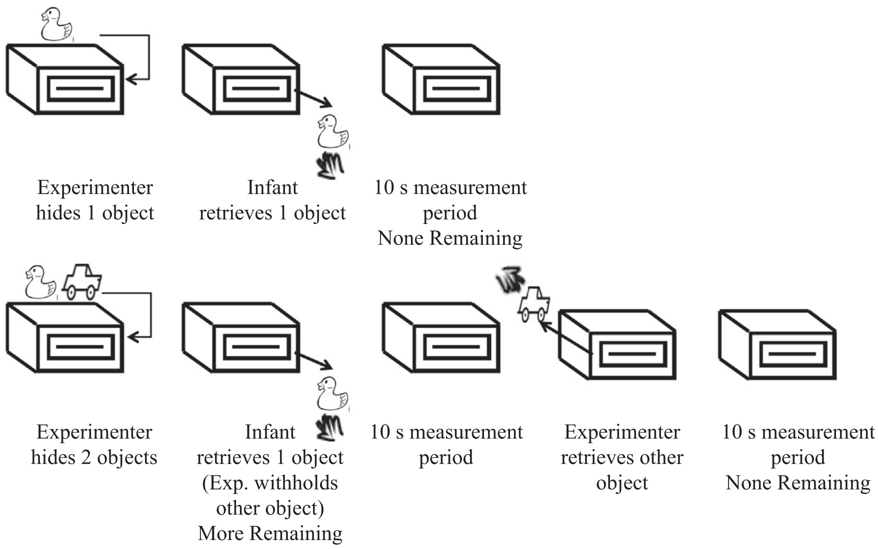

Fig. 1. Example of a 1 vs. 2 Objects block in Experiment 1.

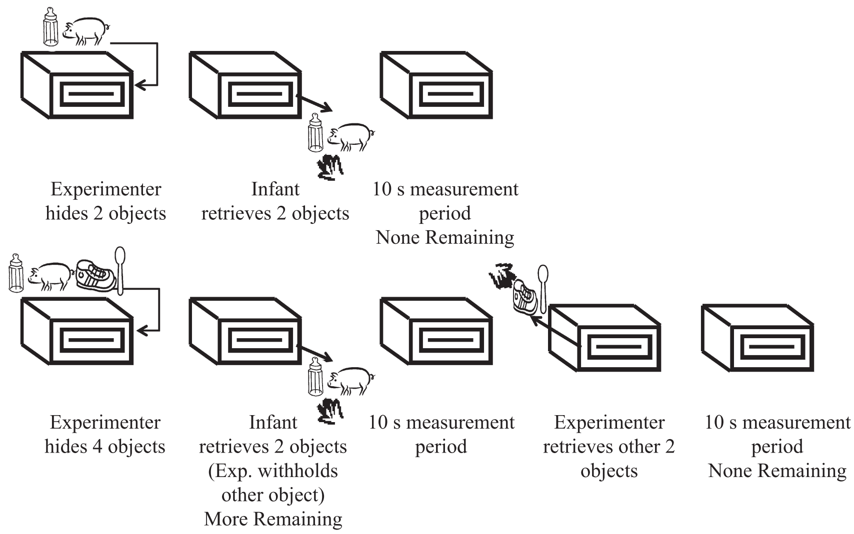

Fig. 2. Example of a 2 vs. 4 Objects block in Experiment 1.

pointed to each and either labeled each object twice (Labeled Objects block) or did not label them (Unlabeled Objects block). For example, in the Labeled Objects block she pointed and said, "Look! A (bottle)! See? A (bottle)! Look! A (pig)! See? A (pig)! Look! A (shoe)! See? A (shoe)! Look! A (spoon)! See? A (spoon)!" In the Unlabeled Objects block she pointed and said, "Look at that! See that? Look at that! See that? Look at that! See that? Look at that! See that?" The experimenter then picked up the objects two at a time and inserted them into the box. As she did this she secretly reached through the opening in the back of the box with her other hand, grasped two of the four objects, and held them out of infants' reach. Infants were allowed to reach in through the front of the box and retrieve the remaining two objects. As soon as infants had retrieved these, the experimenter took them away, placed them out of sight under the table, and the 10-s measurement period began. Throughout these 10 s, the experimenter continued to secretly hold the two remaining objects out of reach in the back of the box. After 10 s, the experimenter said, "Can I help you find something?" and then reached in with her free hand and retrieved the missing objects. She showed the objects to infants, then placed them out of sight under the table.

A final 10-s measurement period then began (4-Objects, None Remaining). This last measurement period was needed in order to interpret infants' behavior on the 4-Objects (More Remaining) measurement periods. If infants had successfully remembered four individual objects, they should keep searching on 4-Objects (More Remaining) periods but should stop searching on 4-Objects (None Remaining) periods (because all of the hidden objects had now been retrieved). In contrast, if infants continued searching on 4-Objects (None Remaining) measurement periods, this would suggest that infants kept searching indiscriminately when working memory capacity had been exceeded.

In the 2 vs. 4 Objects block, accurate memory for the hidden arrays would be revealed by a pattern of little searching on the 2-Objects (None Remaining) measurement period, increased searching on the 4-Objects (More Remaining) period, and little searching again on the 4-Objects (None Remaining) period.

Whether infants first were tested in a 2-Objects (None Remaining) or a 4-Objects (More Remaining) measurement period was counterbalanced across infants. The 4-Objects (None Remaining) measurement periods always followed 4-Objects (More Remaining) measurement periods. Each infant was tested twice with these three measurement periods, and saw the same four objects used throughout the entire 2 vs. 4 block. One pair of objects was randomly chosen for the first 2-Objects (None Remaining) measurement period. These same two objects were also used in the 4-Objects (More Remaining) periods, and were always the first two objects retrieved in the first 4-Objects (More Remaining) measurement period. Another pair of objects was chosen for the second 2-Objects (None Remaining) measurement period. These same two objects were also used in the 4-Objects (More Remaining) periods, and were always the first objects retrieved in the second 4-Objects (More Remaining) measurement period.

2.2.4. Coding

Testing sessions were videotaped and coded offline by two experienced observers who were unaware of whether more objects were expected to remain in the box in any given measurement period. The dependent measure was the amount of time infants searched the box during each 10-s measurement period. Infants were considered to be searching when the second knuckle of either hand was inside the spandex opening of the box. If an infant's hand was still in the box at the end of the measurement period, the experimenter allowed the infant to complete that reach and stopped the measurement period as soon as the infant withdrew their hand from the box. Occasionally infants left their hand in the box but did not appear to be searching actively (e.g., they looked elsewhere in the room or attempted to engage the parent or experimenter). This resulted in a few unusually long events that met our criterion for searching but were unlikely to be meaningfully connected to infants' memory for the box's contents. Therefore, we excluded data from measurement periods in which infants' searches were greater than 2.5 standard deviations from the mean. This resulted in the exclusion of 3% of measurement periods from Experiment 1, 5% from Experiment 2, and 1% from Experiment 3 (consistent with previous experiments using the manual search method). For Experiment 1, inter-observer agreement on the total amount of time each infant spent searching averaged 98%.

2.3. Results

Because each infant was tested with arrays that were expected to be within memory capacity (1 vs. 2 objects) and arrays expected to exceed capacity (2 vs. 4 objects), but only heard objects labeled for one of these two test blocks, we examined infants' searching for each Memory Load (1 vs. 2 or 2 vs. 4 Objects) separately. For each Memory Load we conducted a repeated measures ANOVA that included the within-subject variables of Measurement Period (first None Remaining period, More Remaining period, second None Remaining period) and Pair (first vs. second instance of a measurement period), and the between-subject variable of Labeling Condition (whether infants heard the objects labeled and were reported to know the labels, or did not hear the objects labeled and were reported not to know the labels).

For the 1 vs. 2 Objects block, this analysis yielded a main effect of Measurement Period, $F(2,60) = 4.91$, $p < 0.05$, $\eta_p^2 = 0.14$, with infants searching longer on More Remaining measurement periods than on the other two measurement periods (see further analyses below) (Fig. 3). There was no effect of Labeling Condition, $F(1,30) = 0.001$, $p = 0.99$, $\eta_p^2 < 0.01$, nor any interaction between Measurement Period and Labeling Condition, $F(2,60) = 0.61$, $p = 0.55$, $\eta_p^2 = 0.02$. We did observe a significant effect of Pair, $F(1,30) = 6.84$, $p < 0.05$, $\eta_p^2 = 0.19$, with infants searching longer on the first set of measurement periods than on the second.

For the 2 vs. 4 Objects block, an ANOVA with the same factors yielded a main effect of Measurement Period, $F(2,60) = 15.33$, $p < 0.001$, $\eta_p^2 = 0.34$, with infants searching longer on More Remaining measurement periods than on the other two measurement periods (Fig. 3). There was again no effect of Labeling Condition, $F(1,30) = 0.28$, $p = 0.60$, $\eta_p^2 = 0.01$. There was, however, a significant interaction of Pair by Measurement Period by Labeling Condition, $F(2,60) = 6.36$, $p < 0.01$, $\eta_p^2 = 0.18$, reflecting that infants who did not hear the objects labeled searched longer during the first presentation of the 4-Objects (None Remaining) measurement period than the second.

We more closely examined infants' search patterns with a series of planned tests comparing infants' searching on measurement periods when the box was expected to contain more objects to searching on measurement periods when the box was expected to be empty, for both the 1 vs. 2 and the 2 vs. 4 Objects blocks. First we asked whether, when presented with 1 vs. 2 Objects, infants searched longer when more objects were expected to remain in the box than during either measurement period when the box was empty. We found that they did, for both the first measurement period when no objects should be expected to remain in the box, (More Remaining vs. first None Remaining measurement period: $t(1,31) = 2.58$, $p < 0.05$) and for the second one (More Remaining vs. second None Remaining measurement period: $t(1,31) = 2.62$, $p < 0.05$). In contrast, we found that infants did not search differently on the two measurement periods when the box was empty (first vs. second None Remaining measurement period, $t(1,31) = 0.68$, $p = 0.50$; Fig. 3).

Next we asked whether, when presented with 2 vs. 4 Objects, infants searched longer when more objects were expected to remain in the box than during either measurement period when the box was empty. We found that they did, for both the first measurement period when no objects should be expected to remain in the box, (More Remaining

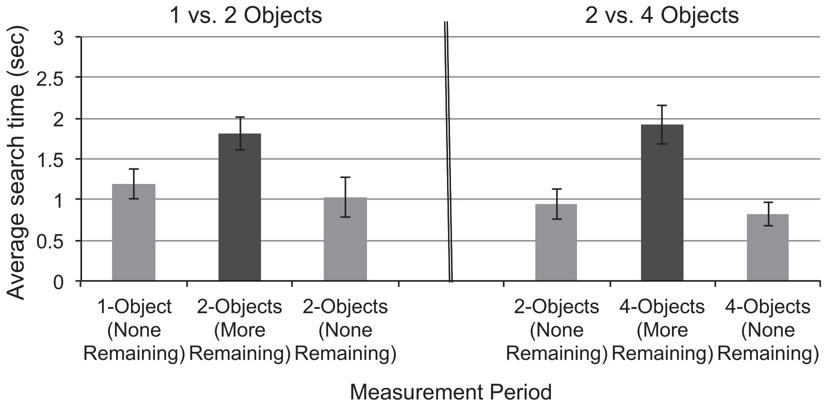

Fig. 3. Infants' searching times in Experiment 1. Bars depict average searching on the first None Remaining, More Remaining, and second None Remaining measurement periods, collapsing across Labeling conditions (±SEM).

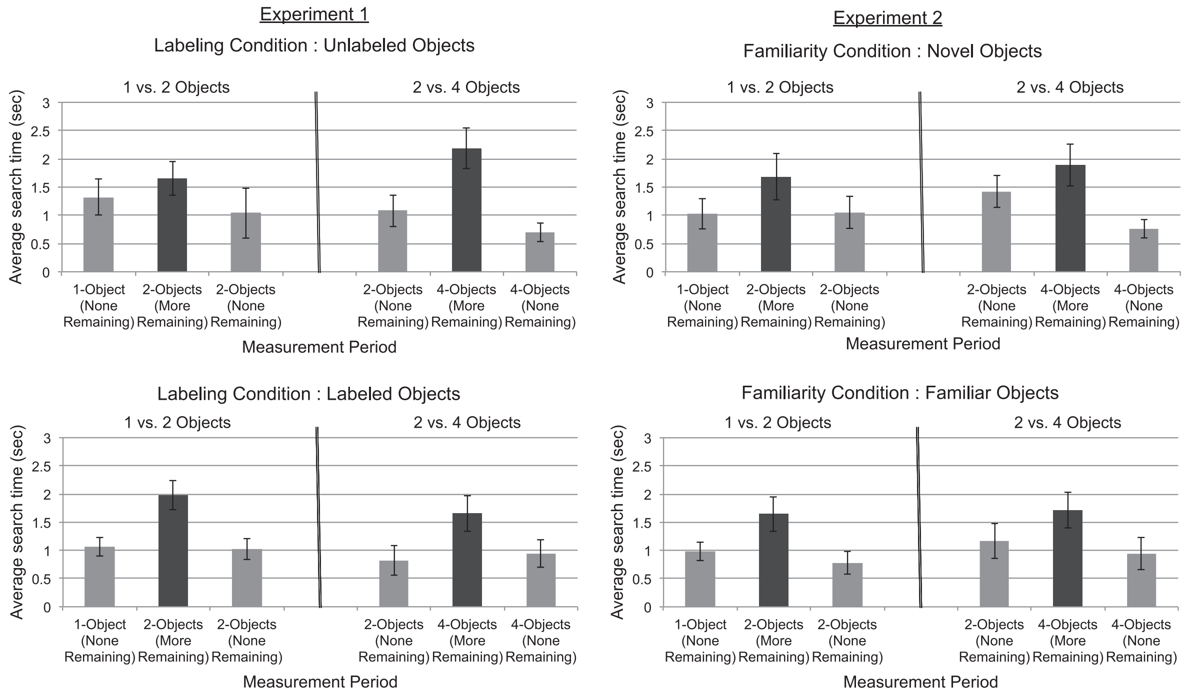

Fig. 4. Infants' searching times in each condition of Experiments 1 and 2. Bars depict average searching for the first None Remaining, More Remaining, and second None Remaining measurement periods (±SEM).

vs. first None Remaining measurement period: $t(1,31) = 4.27$, $p < 0.001$) and for the second one (More Remaining vs. second None Remaining measurement period: $t(1,31) = 4.88$, $p < 0.001$). In contrast, we found that infants did not search differently on the two measurement periods when the box was empty (first vs. second None Remaining measurement period, $t(1,31) = 0.61$, $p = 0.54$; Fig. 3).

Further detail is given in Fig. 4, which reveals that the same general searching pattern was observed for both the Labeled and Unlabeled Objects blocks in both Memory Loads. This suggests that regardless of whether infants had heard objects labeled prior to hiding and were judged by their parents to know the objects' labels, they searched longest on the More Remaining measurement periods for both smaller and larger object arrays.

2.4. Discussion

In previous experiments in which infants were presented with a single group of four or more hidden objects in the absence of chunking cues (Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2008; Rosenberg & Feigenson, 2013), infants failed to continue searching for remaining objects after retrieving any subset of the four. This suggests that infants between 12- and 20-months old are unable to concurrently maintain representations of four identical objects in memory. In contrast, here in Experiment 1, infants who saw four *different* objects hidden continued searching after just two of the four objects had been retrieved. Infants appeared able to successfully remember four unique objects, or at least to successfully discriminate a hidden array of four unique objects from an array of two. This finding supports our prediction that array heterogeneity affects infants' ability to represent supra-capacity arrays. However, we did not observe any effects of labeling. Regardless of whether infants were reported to know the words for the presented objects and heard them labeled just prior to hiding, or were reported not to know the words for the objects and did not hear them labeled, infants successfully kept searching after seeing four objects hidden and retrieving two of them. Although array heterogeneity appeared to affect infants' working memory, this heterogeneity did not require lexical contrast between object labels.

An open question, then, is what kind of array heterogeneity is needed to support infants' ability to represent arrays containing more than three objects. In Experiment 1, infants saw objects that contrasted in category membership (e.g., duck vs. car; animal vs. artifact), in basic visual features including color and texture (e.g., yellow object vs. red object), and, in one condition, in the labels used to describe them (e.g., "duck" vs. "car"). The results of Experiment 1 showed that contrasting labels were not required for infants' success. Next, in Experiment 2, we asked whether prior knowledge of object kinds is needed, or whether simple perceptual contrast between objects would suffice to allow infants to represent supra-capacity arrays. To this end, we showed infants within-capacity and supra-capacity arrays containing the familiar objects from Experiment 1, as well as unfamiliar novel objects that contrasted in their perceptual features.

3. Experiment 2

3.1. Method

3.1.1. Participants

Thirty-two healthy full-term infants participated (10 females; age range = 12 months, 4 days to 13 months, 15 days; mean = 12 months, 25 days). Data from 11 additional infants were excluded (for fussiness [7]; failure to produce the dependent measure on any trial [2]; experimenter error [1]; or having more than two reaches greater than 2.5 SD of the mean [1]).

3.1.2. Materials

The same box was used as in Experiment 1. The objects in the Familiar Objects block were chosen randomly from the set for which parents reported their child did not know the words, but with which infants were expected to be familiar (just as in the Unlabeled Objects block in Experiment 1). Although the results of Experiment 1 suggest that knowing objects' labels does not affect infants' memory for the existence of hidden objects in our task, this precaution ensured that any observed difference between the Familiar and Novel Objects blocks would not be due to infants knowing words for the familiar objects but not the novel ones. The objects in the Familiar Objects block therefore varied between infants. The objects in the Novel Objects block were chosen to be similar to the familiar objects in size, complexity, and inter-object contrast: a plastic deep-fried crab claw from a play food set, a piece of a plastic hair clip, a circular towel holder, and a doll's plastic clip-on skirt. We confirmed the novelty of these objects by presenting them to naïve adults. Adults were unable to reliably identify them, thereby confirming their likely novelty to infants.

3.2. Design and procedure

We again used a modified 2 × 2 design. Each infant was tested in one block containing arrays that were expected to be within working memory capacity, and another block containing arrays expected to exceed capacity. Each infant also was tested in a Familiar Objects block and a Novel Objects block. For half of the infants, the within-capacity arrays (1 vs. 2 Objects) contained Familiar Objects and the supra-capacity arrays (2 vs. 4 Objects) contained Novel Objects. For the other infants, the supra-capacity arrays (2 vs. 4 Objects) contained Familiar Objects and the within-capacity arrays (1 vs. 2 Objects) contained Novel Objects.

As in Experiment 1, within each block there were three measurement periods, each presented twice. For the 1 vs. 2 Objects block these were 1-Object (None Remaining), 2-Objects (More Remaining), and 2-Objects (None Remaining). For the 2 vs. 4 Objects block these were 2-Objects (None Remaining), 4-Objects (More Remaining), and 4-Objects (None Remaining). The sequence of object presentation and timing were exactly as in Experiment 1. Because Experiment 1 found that verbally labeling the objects had no effect on infants' performance with within-capacity or supra-capacity arrays, infants in Experiment 2 never heard the objects labeled. On each presentation, the experimenter presented each object atop the box and said, "Look at that! See that?" Whether infants were tested with the block of within-capacity arrays first or second, and whether they saw familiar objects presented first or second, were counterbalanced across infants. Coding was as in Experiment 1, and inter-observer agreement averaged 98%.

3.3. Results

For each Memory Load we conducted a repeated-measures ANOVA with the within-subject variables of Measurement Period (first None Remaining period, More Remaining period, second None Remaining period) and Pair (first vs. second instance of a measurement period), and the between-subject factor of Object Familiarity (whether infants saw Familiar objects or Novel objects hidden).

For the 1 vs. 2 Object block, this analysis yielded a main effect of Measurement Period, $F(2,60) = 8.36$, $p < 0.01$, $\eta_p^2 = 0.22$, with infants searching longer on More Remaining measurement periods than on the other two measurement periods (see further analyses below). There was no effect of Object Familiarity, $F(1,30) = 0.13$, $p = 0.73$,

$\eta_p^2 = 0.004$, nor any interaction between Measurement Period and Object Familiarity, $F(2,60) = 0.20$, $p = 0.82$, $\eta_p^2 = 0.01$. There was a marginal effect of Pair, $F(1,30) = 3.38$, $p = 0.08$, $\eta_p^2 = 0.10$, with infants searching longer on the first set of measurement periods than the second. The only significant interaction was between Pair and Measurement Period, $F(2,60) = 7.37$, $p < 0.01$, $\eta_p^2 = 0.20$, reflecting that infants searched less when the box was empty during the second presentation of the 1-Object (None Remaining) measurement period.

For the 2 vs. 4 Memory Load, an ANOVA with the same factors yielded a main effect of Measurement Period, $F(2,60) = 8.72$, $p < 0.001$, $\eta_p^2 = 0.23$, with infants searching longer on More Remaining measurement periods than on the other two measurement periods. There was no effect of Object Familiarity, $F(1,30) = 0.06$, $p = 0.81$, $\eta_p^2 < 0.01$. There was a significant interaction of Pair by Measurement Period by Object Familiarity, $F(2,60) = 3.57$, $p < 0.05$, $\eta_p^2 = 0.11$, reflecting that infants who saw novel objects hidden searched longer during the second presentation of the 4-Objects (More Remaining) measurement period, whereas infants who saw familiar objects hidden searched longer during the first presentation of the 4-Objects (More Remaining) measurement period.

As in Experiment 1, we more closely examined infants' search patterns with a series of planned tests comparing infants' searching on measurement periods when the box was expected to contain more objects to searching on measurement periods when the box was expected to be empty, for both the 1 vs. 2 and the 2 vs. 4 Objects blocks. First we asked whether, when presented with 1 vs. 2 Objects, infants searched longer when more objects were expected to remain in the box than during either period when the box was empty. We found that they did, for both the first measurement period in which the box was expected empty (More Remaining vs. first None Remaining measurement period: $t(1,31) = 2.94$, $p < 0.01$) and for the second (More Remaining vs. second None Remaining measurement period: $t(1,31) = 3.97$, $p < 0.001$). In contrast, we found that infants did not search differently on the two measurement periods when the box was empty (first vs. second None Remaining period, $t(1,31) = 0.54$, $p = 0.59$; Fig. 5).

Next we asked whether, when presented with 2 vs. 4 Objects, infants searched longer when more objects were expected to remain in the box than during either period when the box was empty. We found that they did, for both the first measurement period in which the box was not expected to contain any more objects (More Remaining vs. first None Remaining measurement period, $t(1,31) = 2.02$, $p = 0.05$) and for the second (More Remaining vs. second None Remaining measurement period, $t(1,31) = 4.84$, $p < 0.001$). Here we found that infants did search differently on the two measurement periods when the box was expected to be empty, searching longer on the 2-Objects (None Remaining) measurement period than the 4-Objects (None Remaining) measurement period, $t(1,31) = 2.08$, $p < 0.05$.

Further detail is given in Fig. 4, which reveals that the same general searching pattern was observed for both the Familiar and the Novel Objects blocks in both Memory Loads. Regardless of whether infants saw familiar objects or completely novel ones, they searched longest on the More Remaining measurement periods for both smaller and larger object arrays.

3.4. Discussion

Although previous experiments found infants unable to concurrently represent four identical objects in working memory (Barner et al., 2007; Feigenson & Carey, 2003, 2005), Experiment 1 revealed that infants successfully represented arrays of four *contrasting* objects. That is, when presented with heterogeneous arrays containing four distinct objects and seeing just two of these retrieved, infants successfully continued searching for the missing objects, without requiring lexical contrast between the objects' labels. Experiment 2 replicates and extends this result. Again infants succeeded at remembering arrays containing four contrasting objects—this time, regardless of whether the objects were familiar kinds or were completely novel. Thus it appears that simply seeing objects differ from one another in visual features like color and shape affects infants' object memory.

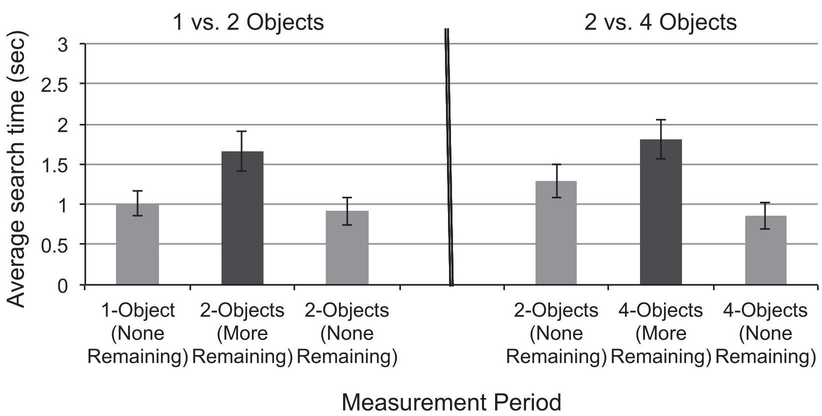

Fig. 5. Infants' searching times in Experiment 2. Bars depict average searching on the first None Remaining, More Remaining, and second None Remaining measurement periods, collapsing across Object Familiarity conditions (±SEM).

However, the mechanism by which array heterogeneity boosted performance remains unclear. One possibility is that array heterogeneity actually expanded infants' memory capacity, allowing infants to store representations of four objects, *qua* distinct individuals. On this account, infants' working memory capacity would change depending on whether the array contained contrasting or identical objects. Alternatively, array heterogeneity might have acted to prevent the catastrophic forgetting observed in previous studies (Barner et al., 2007; Feigenson & Carey, 2003, 2005). Infants presented with heterogeneous object arrays may have been able to maintain representations of objects up to (but not beyond) their typical three-item working memory capacity limit, thereby representing a four-object array as containing three objects, while ignoring or forgetting the fourth object. This would have led infants to succeed with the supra-capacity arrays in Experiments 1 and 2, because after seeing four objects hidden and two of these retrieved, infants could have continued searching the box for the missing third object even without having stored any representation of the fourth. This may be akin to what adults appear to do when presented with supra-capacity arrays (Eng et al., 2005; Luck & Vogel, 1997; Vogel & Machizawa, 2004). We tested this possibility in Experiment 3.

4. Experiment 3

Experiment 3 tested two possible benefits of array heterogeneity by presenting infants with arrays containing four contrasting objects, and allowing them to retrieve either two (as in Experiments 1 and 2) or three of the four. If array heterogeneity allows infants to remember four individual objects, then infants should successfully continue searching the box in both cases. If heterogeneity does not alter capacity but instead prevents catastrophic forgetting—by allowing infants to store up to their capacity (three objects)—then infants should continue searching after seeing four objects hidden and retrieving two of these, but not after seeing four objects hidden and retrieving three.

4.1. Method

4.1.1. Participants

Thirty-six healthy full-term infants participated (19 females; age range = 12 months, 4 days to 13 months, 15 days; mean = 12 months, 25 days). Eighteen infants were randomly assigned to the 3 vs. 4 Objects condition and 18 to the 2 vs. 4 Objects condition. The data from 3 additional infants were excluded (for fussiness [1]; failure to produce the dependent measure on any trial [1], and parental interference [1]).

4.1.2. Materials

The same box was used as in Experiments 1 and 2. Because neither object labeling nor semantic knowledge of object kinds was necessary for the heterogeneity benefit to obtain, infants in Experiment 3 were presented with unlabeled novel objects only. This provided an opportunity to replicate the finding from Experiment 2 of infants' success at remembering arrays containing four contrasting novel objects. Half of the infants tested were presented with the same novel objects used in Experiment 2 (fried crab claw, piece of hair clip, towel holder, and plastic doll skirt). To ensure that the success we observed in Experiment 2 was not due to the particular novel objects used, the other infants were presented with a different set of four novel objects (irregularly shaped grey object, purple plastic circle with protruding spokes, polka-dotted clay object standing on four prongs, and orange doll outfit made of contoured plastic). As in Experiment 2, adults judged these objects to be unfamiliar. Which set of novel objects was used in the 2 vs. 4 and 3 vs. 4 Objects test blocks was counterbalanced across infants.

4.2. Design and procedure

Experiment 3 used a between-subjects design involving only a single test block. We employed this design because when we performed pilot testing using a within-subjects design, we found that infants' searching decreased to near-zero throughout the second test block (regardless of how many objects had been presented), suggesting that showing infants a total of eight novel objects was overwhelming or demotivating. Therefore, for half of the infants we measured searching after they had seen four objects hidden and two of these retrieved (as in Experiments 1 and 2). For these infants, the measurement periods were just as in the 2 vs. 4 Objects block of Experiments 1 and 2: 2-Objects (None Remaining), 4-Objects (More Remaining), and 4-Objects (None Remaining). For the other infants we measured searching after they had seen four objects hidden and three of these retrieved. For these infants, the measurement periods were: 3-Objects (None Remaining), 4-Objects (More Remaining), and 4-Objects (None Remaining). All other aspects of the presentation and coding were as in Experiments 1 and 2, and inter-observer agreement as to infants' search times averaged 93%.

4.3. Results

Infants' searching was examined using a repeated-measures ANOVA with the within-subjects factors of Measurement Period (first None Remaining period, More Remaining period, second None Remaining period) and Pair (first vs. second instance of a measurement period) and the between-subjects factor of Objects Retrieved (whether two or three of the four hidden objects were retrieved prior to the measurement period). This analysis yielded a main effect of Measurement Period, $F(2,68) = 11.90$, $p < 0.001$, $\eta_p^2 = 0.26$, with infants searching generally longer on the More Remaining measurement periods (see further analyses below), and a main effect of Pair, $F(1,34) = 11.53$, $p < 0.01$, $\eta_p^2 = 0.25$, with infants searching longer on the first set of measurement periods than the second. Critically, the main effect of Measurement Period was moderated by a Measurement Period x Objects Retrieved interaction, $F(2,68) = 5.72$, $p < 0.01$, $\eta_p^2 = 0.14$.

We investigated this interaction with a series of planned tests comparing searching on measurement periods when the box was expected to contain more objects to searching when the box was expected to be empty. For the 2 vs. 4 Objects block, we first asked whether infants searched longer when more objects were expected to remain in the box than during either period when the box was empty. We found that infants searched longer after seeing four objects hidden and retrieving just two of them than after seeing two objects hidden and retrieving both of them (More Remaining period vs. first None Remaining period: $t(1,17) = 2.94$, $p < 0.01$), and than after seeing four objects hidden and retrieving all four (More Remaining period vs. second None Remaining period: $t(1,17) = 4.46$, $p < 0.001$). We also found that infants in the 2 vs. 4 Objects block searched differently on the two measurement periods when the box was empty (first vs. second None Remaining measurement period), $t(1,17) = 2.62$, $p < 0.05$, reflecting a general decrease in infants' searching on the second None Remaining trial compared to the first. In contrast, there were no differences between any of the measurement periods for the 3 vs. 4 Objects block. Infants did not search longer after seeing four objects hidden and retrieving just three of them, relative to after seeing two objects hidden and retrieving both of them (More Remaining period vs. first None Remaining period, $t(1,17) = 0.47$, $p = 0.65$), or after seeing four objects hidden and retrieving all four (More Remaining period vs. second None Remaining period, $t(1,17) = 1.20$, $p = 0.25$; Fig. 6). Of the 18 infants who saw four objects hidden and two of these retrieved, 13 exhibited a low–high-low pattern of searching. In contrast, of the 18 infants who saw four objects hidden and three of these retrieved, only 6 showed this pattern.

4.4. Discussion

If array heterogeneity had allowed infants to represent four individual objects, then infants in Experiment 3 should have continued searching when four objects had been hidden and only three of these retrieved. Instead, we found that infants successfully kept searching after seeing four objects hidden and retrieving two of them, but not after retrieving three. This pattern is consistent with infants having represented four-object arrays as containing three objects—that is, with infants storing as many object representations as their working memory capacity would allow, and ignoring or forgetting anything further.

5. General discussion

In the present studies we investigated the curious phenomenon of catastrophic forgetting, in which infants presented with numbers of objects that exceed working memory capacity often appear to forget all of the presented objects rather than just remembering a subset. To summarize our findings, in Experiment 1 we found that infants who saw four objects hidden successfully continued searching after only two of the objects had been retrieved, in contrast to infants in earlier studies. The method we used was identical to that of studies in which infants previously failed—except that we showed infants contrasting objects instead of identical ones. Further, we found that infants did not need to know the objects' verbal labels, nor hear the objects labeled by the experimenter, in order to demonstrate this success. In Experiment 2 we found that the contrasting objects need not even be familiar to infants; infants again successfully continued searching after four objects were hidden and only two retrieved, regardless of whether the objects were familiar kinds (e.g., cat, car) or were entirely novel. Finally, in Experiment 3, we found that array heterogeneity prevented catastrophic forgetting rather than increasing the number of objects infants could maintain in working memory. Infants continued searching after seeing four different novel objects hidden and retrieving two of them, but stopped searching after seeing four different novel objects hidden and retrieving three of them. This suggests that infants represented three out of the four objects in the presented array, and therefore that infants remember heterogeneous object arrays differently from homogeneous arrays.

This benefit of array heterogeneity is unlikely to stem from motivational factors such as a desire to retrieve a particular favorite object seen prior to hiding. In previous

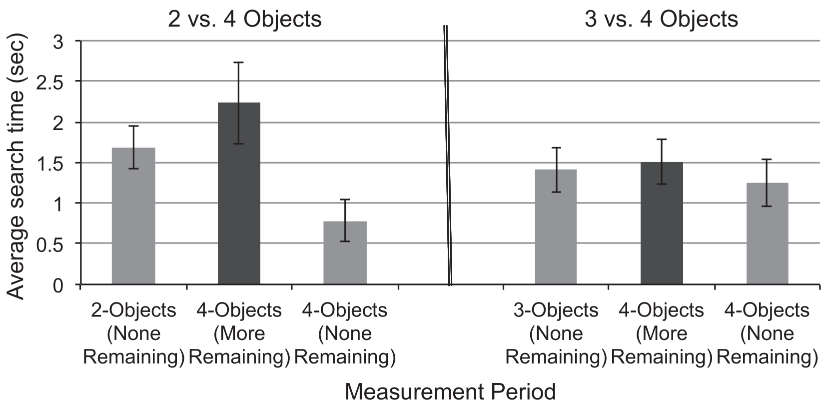

Fig. 6. Infants' searching times in Experiment 3. Bars depict average searching on the first None Remaining, More Remaining, and second None Remaining measurement periods (±SEM).

experiments, infants remembered the existence of three hidden objects, as shown by their continued searching after only one or two of the three objects had been retrieved (Feigenson & Carey, 2003). But they showed little evidence of remembering the objects' identities. For example, when a toy cat, shoe, and bus had been hidden but infants retrieved a car, duck, and brush (i.e., when all of the original objects changed their identities), infants failed to keep searching for the originally hidden objects (despite successfully using these identity changes to guide further searching when arrays of just one or two objects had originally been hidden; Zosh & Feigenson, 2012). In that study, infants presented with three-object arrays only succeeded at using object features to individuate when an object changed radically (from a solid plastic toy to a squishy, non-object blob). These previous results suggest that infants remembered the existence of three hidden objects, but stored only very coarse information about the objects' features (e.g., remembering that a solid object, not a squishy blob, had been hidden, but failing to remember that a shoe, not a duck, had been hidden). The apparent lack of featural detail in infants' representations of a three-object array suggests that infants' persistent searching in Experiments 1–3 when four unique objects had been hidden and only two of these retrieved was not due to infants simply searching until they found one particular remembered object, but rather to their searching for the remembered number of hidden objects. In addition, it seems unlikely that the difference in infants' performance with heterogeneous vs. homogeneous object arrays reflects a general increase in interest or motivation. Infants' overall searching times in Experiments 1–3 were on par with those of previous experiments that used identical objects as stimuli (e.g., Feigenson & Carey, 2003, 2005), and infants in Experiments 1 and 2 who saw one and two objects hidden showed the characteristic pattern of continuing to searching when another object was expected in the box, and decreasing their searching when no further objects were expected. This suggests that simply seeing contrasting objects does not change infants' ability to track arrays that are within the capacity of working memory (e.g., by promoting searching regardless of how many objects had been hidden or retrieved), but does affect memory for supra-capacity arrays.

That array heterogeneity improved infants' working memory performance is in some ways surprising. Previous work has found that heterogeneity impairs preschoolers' success in match-to-sample and counting tasks (Cantlon, Fink, Safford, & Brannon, 2007; Klahr & Wallace, 1976; Mix, 1999, 2008; Siegel, 1974). In these experiments, children performed better when objects within and across arrays looked more similar to each other—a pattern opposite to that observed in our studies. However, the tasks in which array heterogeneity impaired performance required children to attend to the cardinality of the array as a whole—for example, children had to choose the object array that numerically matched a target array. Representing individual objects, *qua* individuals, would not help children succeed at this; only conceiving of the array as a single entity yields the correct answer. This differs from our task, in which children can succeed by tracking individual objects as they are hidden in and retrieved from the box. Thus, heterogeneity may hinder children's ability to represent cardinality, but may enhance their representation of individual objects.

However, other evidence suggests that contrast among items can actually decrease adults' memory for individual objects in change detection tasks (Lin & Luck, 2009). Furthermore, array heterogeneity does not always prevent catastrophic forgetting. In the studies by Oakes and colleagues, 6-month old infants successfully detected a featural change in arrays containing a single object but not in arrays containing multiple objects, all with unique colors, even when every object in the array changed color (Oakes et al., 2006; Oakes, Kovack-Lesh, et al., 2009a; Oakes, Messenger, et al., 2009b; Ross-Sheehy et al., 2003). One possible reason for this is that heterogeneity may only benefit performance when the contrast between objects is represented in working memory. If 6-month old infants can only represent a single object in working memory (Káldy & Leslie, 2005; Ross-Sheehy et al., 2003), then there is no possibility for heterogeneity between remembered objects to affect infants' memory representations. Still, in other studies testing 6-month old infants' memory for the features of two contrasting hidden objects (e.g., a circle and a triangle), infants showed evidence of remembering only the object that had been hidden most recently—that is, they did not exhibit catastrophic forgetting (Kibbe & Leslie, 2011; Káldy & Leslie, 2005). To determine whether the partial memory demonstrated by these infants required array heterogeneity, or also would have obtained with identical objects, will require comparing infants' performance with contrasting vs. identical objects.

An additional possible reason for differences in the observed effects of heterogeneity is the contrast between tasks designed to measure memory for objects' visual features, vs. tasks designed to measure memory for objects' existence. Change detection tasks with both adults and infants measure observers' ability to identify a change to one or more features of an object in an array, or a change to the binding between features and location. Meanwhile, studies like those reported here measure observers' ability to remember that a given number of objects existed in a particular location, regardless of their features. Previous research shows that infants sometimes remember that an object was present, even when its features are forgotten (Kibbe & Feigenson, submitted for publication; Kibbe & Leslie, 2011; Zosh & Feigenson, 2012), raising the possibility that heterogeneity may differently affect infants' memory for objects' existence and for their features. In addition, the influence of array heterogeneity at different retention intervals remains to be explored. For example, change detection tasks with infants and adults typically involve memory retention intervals of one second or less, whereas object occlusion tasks like those in the present experiments involve retention intervals of several seconds (for evidence that working memory representations can persist for many seconds, see Gilmore & Johnson, 1995; Noles, Scholl, & Mitroff, 2005; Zhang & Luck, 2008). Further work is needed to examine how heterogeneity affects memory in different types of visual tasks, and at different timescales.

Although more research is needed to characterize the effects of heterogeneity on memory in these different circumstances, the mechanism by which inter-item contrast affects memory at all still remains for discussion. This issue has been much discussed in the case of verbal working memory, where research with adults has consistently found a benefit for heterogeneous items. For example, adults are better at remembering lists of items from different categories (e.g., words and digits), than lists of items from the same category (Bunting, 2006; see also Keppel & Underwood, 1962), and highlighting the differences between items during encoding can improve memory performance (Hunt & McDaniel, 1993). This benefit is typically attributed to a reduction in the proactive interference that accumulates between representations of similar items. Indeed, the ability to avoid proactive interference between memory items appears critical to successful storage: adults' working memory capacity can be predicted by performance on a task measuring susceptibility to proactive interference (Whitney, Arnett, Driver, & Budd, 2001), and individuals with lower working memory capacities appear to be more susceptible to interference across a variety of tasks (Conway & Engle, 1994; Kane & Engle, 2000; Rosen & Engle, 1998; see Jonides & Nee, 2006 for a review), as well as more likely to fail to inhibit representations of irrelevant stimuli (Conway, Cowan, & Bunting, 2001; Vogel, McCollough, & Machizawa, 2005).

The reduction of proactive interference among contrasting items offers one possibility for the source of the heterogeneity benefit we observed in Experiments 1–3. However, a puzzle still remains, in that the interference account does not seem to explain the abrupt nature of infants' failure to remember more than three identical items (or their success at remembering three out of four contrasting items, as in our experiments). Proactive interference might be expected to cause a more gradual decrement in infants' memory performance as the number of identical items in the array increases. One possibility is that proactive interference may only arise when working memory capacity is exceeded. Some previous studies have found that adults presented with lists of varying lengths experienced proactive interference only for lists that exceeded capacity (Cowan et al., 2005; Halford, Maybery, & Bain, 1988; but see Wickens, Born, & Allen, 1963). If infants only suffer the effects of proactive interference when presented with arrays exceeding their 3-item working memory capacity, then heterogeneous objects may specifically benefit their ability to represent supra-capacity arrays.

Even so, we note that the reduction of proactive interference may not affect infants' memory performance in a straightforward way. Namely, accounts of proactive interference assume that conceptual and/or featural information is stored as part of an item representation; the less these features overlap across items, the less the inter-item interference and the better the memory performance. However, the finding that infants slightly older than those tested here stored only very coarse memories of three hidden objects (Zosh & Feigenson, 2012) suggests that, for infants, heterogeneity may not lead to memory representations that retain their featural distinctiveness. Instead, heterogeneity may operate during an earlier stage, perhaps by making it more likely that a subset of the objects in a four-object array will be encoded into memory at all. Alternatively, heterogeneous arrays may allow for more distinctive representations to be maintained in memory, but this conceptual or featural information may be lost or not accessed when infants later retrieve the representations (Simons & Rensink, 2005). Given that infants in more passive looking-time tasks have shown success at remembering the identities of three objects at once (Rose et al., 2001; Ross-Sheehy et al., 2003), it may be that more demanding, goal-directed tasks—like the manual search task used here, which requires that infants not just discriminate objects but also that they individuate—lead to the loss of specific identity information. Less demanding tasks might reveal that heterogeneity helps infants remember not only the number of objects in a scene, but also the objects' identities. Thus, further work is needed to determine exactly which aspects of a supra-capacity array are maintained in infants' memory, and under what conditions.

To conclude, the present experiments shed light on a puzzling finding in the development of working memory. Although infants and young toddlers often demonstrate working memory capacity limits similar to those of adults, they have shown a strikingly different pattern of failure when memory capacity is exceeded: instead of remembering as many items as they can and ignoring the others, they experience catastrophic forgetting. That is, they fail to maintain a representation of *any* of the items in the array. Here, in three experiments, we show that catastrophic forgetting can be avoided by presenting infants with arrays of contrasting rather than identical objects. When shown four unique objects, the infants in our studies appeared to represent three of them, much as adults do. This suggests that the nature of forgetting depends, in part, on what is being remembered.

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