Developmental Science

Developmental Science 16:4 (2013), pp 610–621 DOI: 10.1111/desc.12055

PAPER

Infants hierarchically organize memory representations

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Abstract

Throughout development, working memory is subject to capacity limits that severely constrain short-term storage. However, adults can massively expand the total amount of remembered information by grouping items into chunks. *Although infants also have been shown to chunk objects in memory, little is known regarding the limits of this ability. In particular, it remains unknown whether infants can create more complex memory hierarchies, binding representations of chunks into still larger chunks in recursive fashion. Here we tested the limits of early chunking, first measuring the number of items infants can bind into a single chunk and the number of chunks infants can maintain concurrently, and then, critically, whether infants can embed chunked representations into larger units. We tested 14-month-old infants' memory for hidden objects using a manual search task in which we manipulated memory load (the number of objects infants saw hidden) and the chunking cues provided. We found that infants are limited in the number of items they can chunk and in the number of chunks they can remember. However, we also found that infants can bind representations of chunks into 'superchunks'. These results suggest that hierarchically organizing information strongly affects working memory, starting in infancy.*

Introduction

Hierarchical organization of information is critical to many disciplines. From molecules and atoms to kingdoms and phyla, hierarchies support information compression by nesting each level of representation within a broader level. One reason hierarchies can play this explicit role in our scientific concepts is that they structure human thought more generally, particularly in the everyday context of memory.

Much evidence has shown that working memory (WM), which allows information to be held in a state of heightened activation for current processing, is strikingly limited. Whether constrained by the absolute number of items (estimated at three or four) or the total amount of information that can be maintained, there is general agreement that adults' WM capacity is surprisingly small (e.g. Alvarez & Cavanagh, 2004; Cowan, 2001; Luck & Vogel, 1997; Sperling, 1960). One solution to the problem of storing information in a limited capacity system is to bind or 'chunk' individual items into more efficient, hierarchically structured representations. Adults do this widely when grouping items in memory (e.g. Cowan, 2001; Gobet & Clarkson, 2004; Mandler, 1967; Miller, 1956; Simon, 1974). For example, adults recall phone and credit card numbers in distinct chunks, each containing three or four digits. Sometimes chunks rely on semantic knowledge, as when chess experts remember configurations in meaningful groups rather than individual chess pieces (Chase & Simon, 1973). Other times no prior semantic knowledge is required, as in the case of phone numbers. But in all cases, chunking requires representing both the larger structure (the chunk) and its components (the individual items).

The power of hierarchical representation is most striking when chunking involves multiple representational levels. For example, one well-studied participant, SF, increased his memory span to nearly 80 random digits by creating elaborate mental hierarchies (Chase & Ericsson, 1981; Ericsson, Chase & Faloon, 1980). SF grouped up to four digits into chunks, then nested these within larger 'superchunks'. For example, because SF

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was an accomplished runner, he remembered the digits '3', '4', '9', and '2' as '3 minutes, 49 point 2 seconds', which he classified as 'a near world record time for running a mile'. Slightly slower times were subsumed under the category 'under 4-minute mile' and both categories were subsumed under the category 'mile running times'. SF's spontaneous discovery of this strategy let him to vastly exceed typical WM limits.

Research suggests that chunking is used early in development by school-aged children (Rosner, 1971; Moely & Jeffrey, 1974; Sodian, Schneider & Perlmutter, 1986), and even by infants. Infants from 10 months to 2 years old exhibit a WM capacity limit of about three items, much like adults (Barner, Thalwitz, Wood & Carey, 2007; Feigenson & Carey, 2003, 2005; Ross-Sheehy, Oakes & Luck, 2003). This limit obtains with simple and complex stimuli, and with simultaneous and sequential presentation. Like adults, infants can increase the amount of remembered information via chunking. In one study, 14-month-old infants saw four identical objects hidden in a box, and then were allowed to retrieve a subset of these (experimenters surreptitiously withheld one, two, or three out of reach in the back of the box). Strikingly, infants did not continue searching for the remaining object(s), suggesting that they failed to represent four objects concurrently (despite success at remembering starting arrays of one, two, and three). Yet, when infants saw the same four objects grouped into two spatially separated groups of two, infants who retrieved a subset of the four now continued searching for the remaining objects (Feigenson & Halberda, 2004).

These findings suggest that from infancy onward, memory can be expanded through hierarchical organization. However, it remains unknown how powerful this early chunking is. Whereas adults can construct elaborate mental hierarchies containing as many as 80 items stored across multiple levels of representation (Chase & Ericsson, 1981; Kliegl, Smith, Heckhausen & Baltes, 1987), infants' abilities may be more modest. Previous data show that infants can perform first-order chunking, storing two levels of representations (the individual object and the chunk). But it is unclear whether, for infants, the output of one chunking operation can itself serve as the input to another chunking operation, in recursive fashion. Can infants bind multiple chunks into a larger 'superchunk'? If infants, like adults, can also use higher-order chunking to further expand their WM capacity, this would provide a powerful tool for information storage.

We examined infants' chunking abilities in four experiments. First, we tested the limits of first-order chunking by measuring the maximum number of objects 14-month-old infants can bind into a chunk, as well as the maximum number of chunks infants can remember concurrently. Previous work showed that 14-month-olds can represent two or three chunks when each chunk contains two objects. Experiment 1 asked whether infants also can represent *two* chunks of *three* objects each. Experiment 2 asked whether infants can represent *four* chunks of *two* objects each. To preview, although we replicated the finding that infants successfully represent two chunks of two objects each, we found that infants failed to represent either two chunks of three objects each, or four chunks of two objects each.

Having established the upper limits of infants' first-order chunking, we then asked whether infants can remember larger numbers of objects by maintaining three nested levels of representation – the individual object, the chunk, and the superchunk. Experiment 3 asked whether infants could remember eight objects when provided with spatiotemporal cues to chunk the objects into three levels of memory representation. We presented eight objects divided into two superchunks, each containing two chunks, with each chunk itself containing two individual objects. Finally, Experiment 4 asked whether infants could again remember two superchunks, each containing two chunks of two objects, this time using a combination of spatial and featural information.

Experiment 1

We used a manual search task to measure the number of objects that infants can remember concurrently (cf. Barner *et al.*, 2007; Feigenson & Carey, 2003, 2005). Infants watched a number of objects hidden in a box, and were allowed to retrieve either all or just a subset of them. We then measured how long infants searched the box. If infants successfully remembered how many objects were hidden, they should search longer when only a subset of the objects was retrieved than when of all the objects were retrieved.

This method has revealed that 14-month-olds successfully represent six total objects when these are chunked into three sets of two objects each (Feigenson & Halberda, 2008). Infants first saw three spatially separated sets each containing two objects, then saw an experimenter pick up all six objects and hide them in the box, two at a time. When, moments later, infants saw four of these six objects retrieved from the box, they successfully continued searching the box for the remaining two objects. In contrast, when infants initially saw the same six objects presented as one set prior to hiding, then saw four of the six retrieved, they failed to keep searching (Figure 1a). Hence infants appeared unable to remember six individual objects, but could remember three chunks of two. However, this study does not reveal

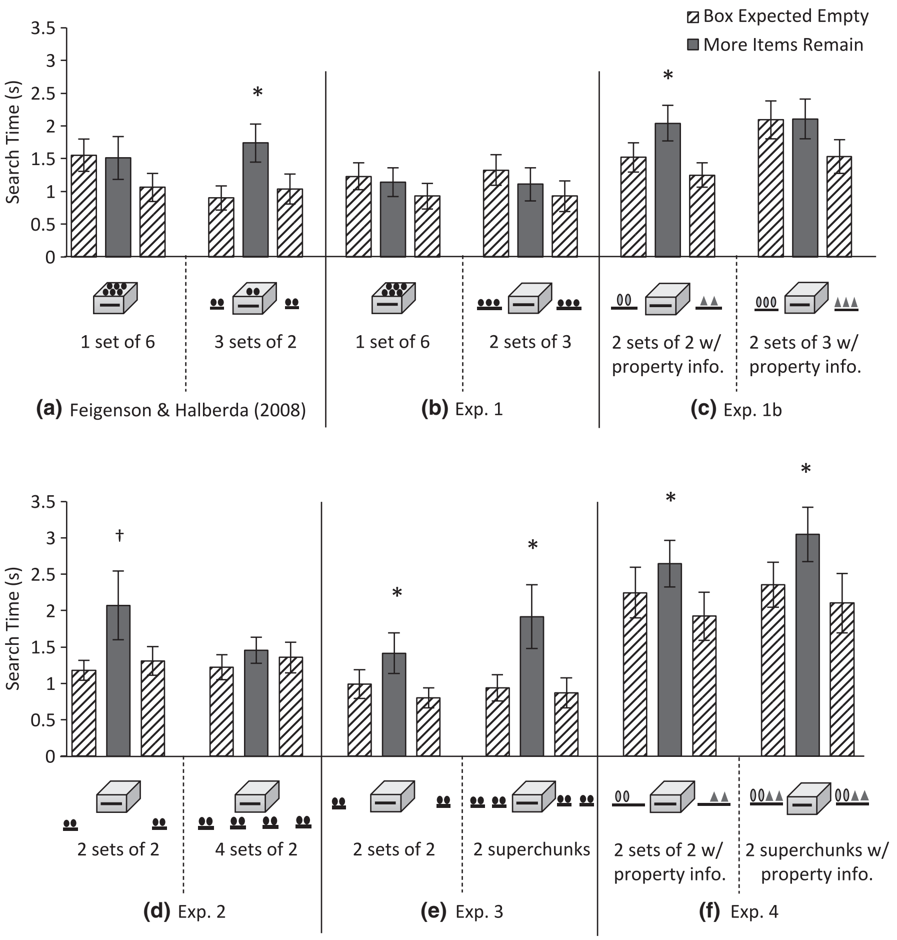

Figure 1 *Schematic of the stimulus presentation and mean searching time (± 1 standard error) in all experiments (panels b–f), and in Experiment 4 by Feigenson and Halberda (2008). * indicates a difference score (searching in More Items Remain measurement periods minus searching in collapsed Box Expected Empty measurement periods) greater than chance at $p \leq .05$; † indicates a difference score marginally greater than chance at $p < .1$.*

the maximum number of objects infants can bind into a chunk. Therefore, in Experiment 1 we asked whether infants could again represent six total objects, now as two chunks of three. Although adults can chunk three items together (Chase & Simon, 1973; Cowan, Chen & Rouder, 2004; Ericsson *et al.*, 1980), there is currently no evidence that infants can bind more than two items into a chunk.

Method

Participants

Twenty-two healthy, full-term infants participated (age range: 13.5–15 months; *M* = 14 months, 1 day; eight females). Infants received a small gift (T-shirt, book, or toy) for participation.

Stimuli

Identical yellow balls (4 cm diameter) were presented atop two 18 × 11.5 cm platforms, or atop a black foam-core box (42 × 25 × 11.5 cm). The box had a 13 × 7 cm spandex-covered opening in the front, with a slit across its width through which infants could reach. The box's rear face contained a concealed opening to allow the experimenter to surreptitiously withhold objects on critical trials.

Procedure

Infants sat in a highchair at a child-sized table, with the experimenter kneeling to one side. Infants first were familiarized to the hiding and retrieval of objects with a set of plastic keys. Once infants had successfully obtained the keys at least once, the test trials began.

For all test trials, the box was placed on the table approximately 10 cm from infants, with the two presentation platforms placed 5 cm away on either side (in line with the box's front face). Infants participated in two test blocks: in one infants saw six objects presented in a single set (with no chunking cues) and in the other infants saw the same six objects presented as two sets of three (Figure 1b). Block order was counterbalanced across infants.

The ***1 Set of 6 Block*** compared infants' searching when more objects should be expected to remain in the box (after six objects had been hidden and only four retrieved) to searching when the box should be expected to be empty (after four objects had been hidden and all four retrieved, and after six objects had been hidden and all six retrieved). The block contained three types of measurement periods.

4 Hidden, None Remaining periods measured infants' searching after they had seen four objects hidden in two sets of two, and had seen all four objects retrieved. Infants watched the experimenter place two identical balls on a platform on one side of the box, and two identical balls on the platform on the other side. Whether balls were placed on the left or right platform first was counterbalanced. Next, the experimenter picked up both balls from one platform and inserted them into the box in a single motion, then picked up both balls from the other platform and inserted them. Afterwards, infants were allowed to reach in and retrieve the balls. Typically infants immediately retrieved one or two of the four, after which the experimenter quickly helped retrieve the remaining balls (this was done on all trials to minimize the duration between object hiding and retrieval: approximately 9 seconds across all trial types in all experiments). The experimenter then showed infants all four balls in her hand, and made sure infants watched as she placed them out of sight under the table. The box was left in place. A 10-second measurement period followed in which the experimenter looked down to avoid cuing infants, and infants' searching (defined as the second knuckle of either hand entering the box) was measured. After 10 seconds, the experimenter said 'Good job', and began the next trial.

6 Hidden, 2 Remaining periods measured infants' searching after they had seen a single set of six objects hidden, and just four of these retrieved. The experimenter placed six balls atop the box using two hand movements. Next she picked up three balls and inserted them into the box, then picked up and inserted the remaining three. Critically, during these trials the experimenter secretly reached through the concealed opening in the box's rear face, grasped two of the six inserted balls, and held these out of infants' reach at the back of the box. Infants were then allowed to reach into the box, where they could retrieve any of the four balls not being withheld. The experimenter then quickly reached through the front of the box and retrieved all the remaining balls from the four not being withheld, showed them to infants, and made sure infants watched as she placed all four retrieved balls out of sight under the table. A 10-second measurement period – *6 Hidden, 2 Remaining* – followed in which the box was left in place and searching was measured.

After 10 seconds the experimenter retrieved the remaining two balls that had been withheld, showed them to infants, and placed them out of sight under the table. A final 10-second measurement period followed – *6 Hidden, None Remaining* – during which the box was empty and infants' searching was again measured. As in previous studies using this method (Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2004, 2008), this last measurement period was included to ensure that any success at continuing to search on *6 Hidden, 2 Remaining* periods was not due to infants having an unspecified expectation that there was more to obtain in the box, without a commitment as to *how many* more. Each of the three measurement periods was presented twice. *6 Hidden, None Remaining* periods always followed *4 Hidden, 2 Remaining* periods, but otherwise order was counterbalanced between infants.

The ***2 Sets of 3 Block*** contained the same three types of measurement periods as the 1 Set of 6 Block. However, unlike in the 1 Set of 6 Block, the array of six objects was always presented with chunking cues.

4 Hidden, None Remaining measurement periods were identical to those in the 1 Set of 6 Block.

6 Hidden, 2 Remaining measurement periods were identical to those in the 1 Set of 6 Block, except that the six balls were placed on platforms to either side of the box instead of on top. The experimenter placed three balls on one platform and then three balls on the other, then picked up and inserted each set of three into the box. Whether balls were first presented on the left or right platform was counterbalanced. All other aspects of timing and presentation were as in the 1 Set of 6 Block.

6 Hidden, None Remaining measurement periods were identical to those in the 1 Set of 6 Block.

As with the 1 Set of 6 Block, each measurement period was presented twice. *6 Hidden, None Remaining* periods always followed *6 Hidden, 2 Remaining* periods, but otherwise order was counterbalanced between infants.

Results and discussion

All trials were coded offline by two observers, with the primary observer blind to whether any objects were expected to remain in the box on any given trial. Average inter-observer agreement across all experiments was .94.

First, we predicted no difference in infants' searching across the different measurement periods when no objects were expected to remain in the box (i.e. when infants had already seen all of the hidden objects retrieved). This prediction was confirmed, both for the 1 Set of 6 Block (searching on *4 Hidden, None Remaining* periods did not differ from searching on *6 Hidden, None Remaining* periods, $t(21) = 1.23$, $p = .23$) and the 2 Sets of 3 Block (searching on *4 Hidden, None Remaining* periods did not differ from searching on *6 Hidden, None Remaining* periods, $t(21) = 1.44$, $p = .16$). Because searching did not differ across these trials we collapsed the two types of 'None Remaining' scores within each block.

Next, we asked whether infants remembered the total number of objects hidden, searching longer when objects were expected to remain in the box than when it was expected to be empty. In the 1 Set of 6 Block, when no chunking cues were provided, we found that infants did not search longer on the *6 Hidden, 2 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = -.06$, $p = .95$). In the 2 Sets of 3 Block, when chunking cues were provided, infants also failed to search longer on the *6 Hidden, 2 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = .36$, $p = .72$; Figure 1b). Across both blocks, infants failed to continue searching when six objects had been hidden and four retrieved.

As expected, infants in Experiment 1 failed to remember a single set of six objects in the absence of chunking cues (replicating a similar failure by Feigenson & Halberda, 2008). Our results also suggest that although infants can successfully chunk four objects into two sets of two (Feigenson & Halberda, 2004, 2008) and chunk six objects into three sets of two (Feigenson & Halberda, 2008) (Figure 1a), 14-month-olds have difficulty chunking six total objects into two sets of three.

Before concluding that we identified the maximum number of individual objects infants can bind into a chunk (at least with this age group and paradigm), we wished to replicate the findings of Experiment 1. Therefore, Experiment 1b had two aims. First, infants' failures in Experiment 1 leave open the possibility that this group of infants was not motivated to remember objects in our task. Consequently, in Experiment 1b we tested each infant not only with a block of two sets of three objects, but also with a block of two sets of two objects (with which infants have demonstrated success in previous studies). Second, previous studies found that infants can use both spatial and conceptual/perceptual cues to motivate chunking (Feigenson & Halberda, 2008), and that younger infants (7-month-olds) sometimes need multiple redundant cues in order to chunk (Moher, Tuerk & Feigenson, 2012). Therefore in Experiment 1b we asked whether infants might succeed at remembering two sets of three objects if given multiple redundant chunking cues. Infants saw two sets of three spatially separated objects (as in Experiment 1), with the sets also contrasting in kind membership, color, and shape. Presenting these redundant chunking cues provides a stronger test of infants' ability (or inability) to represent three-object chunks.

Experiment 1B

Method

Participants

Twenty-two healthy, full-term infants participated (age range: 13.5–15 months; $M = 14$ months, 5 days; 12 females). Four additional infants were excluded for experimenter error (1) or failure to search on any trial (3).[1]

Stimuli

The same box and platforms were used as in Experiment 1. Instead of balls, stimuli for one block were green toy frogs (3.5 cm × 3 cm × 5 cm) and white toy brushes (10 cm × 2.5 cm × 3.5 cm). In the other block infants saw yellow toy cats (2 cm × 3 cm × 7 cm) and red toy cars (7 cm × 2.5 cm × 2 cm). Half of the infants saw frogs and brushes in the first block and cats and cars in the second; half saw the reverse.

Procedure

In one test block infants saw four objects presented as two sets of two, and in the other infants saw six objects presented as two sets of three (Figure 1c). Block order was counterbalanced across infants.

The ***2 Sets of 2 Block*** compared infants' searching when more objects should be expected in the box (after four objects had been hidden and only two retrieved) to searching when the box should be expected to be empty (after two objects had been hidden and both retrieved, and after four objects had been hidden and all four

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[1] Infants who failed to search on any trial typically appeared wary of reaching into the box. Because these infants refused to produce the dependent measure, they were excluded from analysis.

retrieved). The block contained three types of measurement periods.

2 Hidden, None Remaining periods measured searching after infants had seen two objects hidden and both objects retrieved. Infants watched the experimenter place a frog on one platform and a brush on the other (half of infants saw a cat and a car instead; only the frog/ brush presentation is described for brevity). The side and order of placement were counterbalanced. Next the experimenter picked up each object and placed it into the box. Infants were then allowed to reach into the box to retrieve the objects. If infants retrieved just one, the experimenter quickly helped retrieve the other. She then showed infants both retrieved objects and made sure they watched as she placed them out of sight under the table. The box was left in place. A 10-second measurement period followed in which infants' searching was measured.

4 Hidden, 2 Remaining periods measured searching after infants had seen four objects hidden and two objects retrieved. Infants watched the experimenter place two frogs on one platform and two brushes on the other, with order and side of placement counterbalanced. The experimenter then picked up each object pair and placed it into the box. While placing the objects, she secretly reached through the concealed opening in the back of the box and withheld two of the four objects (one frog, one brush). Infants were then allowed to reach in and retrieve the two objects not being withheld. If infants did not immediately retrieve both, the experimenter helped. The experimenter then took these two objects and placed them out of sight under the table. A 10-second measurement period followed.

After 10 seconds the experimenter retrieved the remaining two objects being withheld (one frog, one brush), showed them to infants, and placed them out of sight under the table. A final 10-second measurement period – *4 Hidden, None Remaining* – followed. Each of the three measurement periods was presented twice. *4 Hidden, None Remaining* periods always followed *4 Hidden, 2 Remaining* periods, but otherwise order was counterbalanced between infants.

The ***2 Sets of 3 Block*** compared infants' searching on trials when more objects should be expected in the box (after six objects had been hidden and only four retrieved) to their searching on trials when the box should be expected empty (after four objects had been hidden and four retrieved, and after six objects had been hidden and six retrieved).

The three types of measurement period were as in the 2 Sets of 3 Block of Experiment 1, except that frogs were placed on one platform and brushes on the other (rather than identical balls on both). On *4 Hidden, None Remaining* measurement periods infants saw two frogs and two brushes hidden, saw all four retrieved, and then were allowed to search the box. On *6 Hidden, 2 Remaining* periods infants saw three frogs and three brushes hidden, saw two frogs and two brushes retrieved, and then were allowed to search. On *6 Hidden, None Remaining* periods infants saw the remaining frog and brush from the previous period retrieved (such that the box was now empty), and then were allowed to search. Each of the three measurement periods was presented twice. *6 Hidden, None Remaining* periods always followed *4 Hidden, 2 Remaining* periods, but otherwise order was counterbalanced between infants.

Results and discussion

First, we predicted that there would be no difference in searching across the different measurement periods when no objects were expected to remain in the box. This was confirmed for the 2 Sets of 2 Block ($t(21) = 1.20$, $p = .25$); therefore we collapsed across both types of 'None Remaining' scores for this block. We then asked whether infants searched longer when objects were expected to remain in the box than when the box was empty. Indeed, infants searched significantly longer on the *4 Hidden, 2 Remaining* periods than the collapsed *None Remaining* periods ($t(21) = 2.88$, $p = .009$), demonstrating that they successfully remembered the hidden objects (Figure 1c).

We found that in the 2 Sets of 3 Block, infants did not search equally across the two types of *None Remaining* measurement periods, searching longer after seeing four objects hidden and four retrieved (2.09 seconds) than after seeing six objects hidden and six retrieved (1.54 seconds) ($t(21) = 2.24$, $p = .036$). Therefore we did not collapse these. Instead we directly compared infants' searching on *6 Hidden, 2 Remaining* periods with searching on each of the other two measurement periods. Infants did not search longer on *6 Hidden, 2 Remaining* periods than on *4 Hidden, None Remaining* periods ($t(21) = .06$, $p = .96$), but did search longer on *6 Hidden, 2 Remaining* periods than on *6 Hidden, None Remaining* periods ($t(21) = 2.28$, $p = .03$; Figure 1c).

It is difficult to interpret this finding due to the lack of difference between *6 Hidden, 2 Remaining* periods and *4 Hidden, None Remaining* periods. Although this could indicate a weak success at remembering two sets of three, it could also reflect that infants searched least on *6 Hidden, None Remaining* periods simply because the most time had elapsed between these measurement periods and the initial hiding of objects. Therefore, to investigate the possibility of success at remembering two sets of three, we examined infants' search patterns across Experiments 1 and 1b. This gave us a larger sample and more power to detect possible success. A 2 (Experiment: 1 versus 1b) × 2 (Measurement Period: *6 Hidden, 2 Remaining* versus *None Remaining*) analysis of variance revealed no main effect of Measurement Period ($F(1,42) = .60$, $p = .44$), indicating that across the two experiments, infants did not search longer after six objects had been hidden and four retrieved than when four or six objects had been hidden and all of them retrieved. Nor was there any interaction between Experiment and Trial Type ($F(1,42) = .77$, $p = .38$), indicating that infants were no more successful at chunking two sets of three when provided with both types of chunking cues (Experiment 1b) than with spatial cues only (Experiment 1).

Together, Experiments 1 and 1b replicate two previous findings regarding infants' chunking abilities. First, they show that infants failed to represent a single set of six objects. Second, they show that infants successfully represent four total objects when presented as two sets of two. These experiments also offer new insight into the limits of early chunking. They suggest that infants are unable to represent six objects as two sets of three, either when provided with spatial cues only (Experiment 1) or spatial plus featural/conceptual cues (Experiment 1b). Since infants in previous experiments successfully represented six objects as three sets of two (Feigenson & Halberda, 2008), this suggests an upper limit on the number of individual objects infants can bind into a chunk, at least at this age and within this paradigm. That limit appears to be two.

Experiment 2

Experiments 1 and 1b suggest that infants are limited in the number of objects they can bind into a chunk. However, they leave open how many chunks infants can represent concurrently. Previous work found that infants can represent three sets of two objects each (Feigenson & Halberda, 2008). In Experiment 2 we asked whether they also can represent *four* sets of two objects each. As a check of our methods, as in Experiment 1b, infants saw two sets of two objects each (a presentation with which infants have previously succeeded; Feigenson & Halberda, 2004, 2008; Experiment 1b), as well as the novel presentation of four sets of two objects each.

Method

Participants

Twenty-two infants participated (age range: 13.5–15 months; M = 14 months, 7 days; 11 females). Four additional infants were excluded for fussiness (1) or failure to search on any trial (3).

Stimuli

The box and balls were those used in Experiment 1. Four smaller 12 cm × 10 cm platforms replaced those from Experiments 1 and 1b.

Procedure

Infants participated in two test blocks. In one, four objects were presented as two sets of two, and in the other eight objects were presented as four sets of two (Figure 1d). Block order was counterbalanced.

The ***2 Sets of 2 Block*** tested infants' ability to remember four objects as two sets of two. This was nearly identical to the 2 Sets of 2 Block in Experiment 1b, except that identical yellow balls replaced the frogs and brushes, and hence only spatiotemporal chunking cues were available. Platforms were placed 8 cm from either side of the box, 3 cm in front of the box's front edge. Measurement periods were just as in Experiment 1b: *2 Hidden, None Remaining*; *4 Hidden, 2 Remaining*; and *4 Hidden, None Remaining*.

The ***4 Sets of 2 Block*** tested infants' ability to remember four sets of two objects each (eight total objects). Four presentation platforms were arranged in an equi-spaced row in front of the box, 8 cm apart and 3 cm in front of the box's front face.

On *4 Hidden, None Remaining* measurement periods the experimenter placed two balls on the left-most platform and two on the right. She then inserted the balls into the box two at a time, and infants were allowed to retrieve all four. As in Experiments 1 and 1b, the experimenter helped retrieve any balls that infants did not immediately retrieve. A 10-second measurement period followed during which the box was left in place and searching was measured.

On *8 Hidden, 4 Remaining* measurement periods the experimenter placed two balls on each of the four platform, then inserted the pairs sequentially into the box. Infants were allowed to retrieve four of the eight hidden balls (while the experimenter secretly withheld the other four out of reach at the back of the box). If infants did not immediately retrieve the four balls within reach, the experimenter assisted. The experimenter then immediately took away all of the retrieved balls, and a 10-second measurement period followed during which the box was left in place and searching was measured. After 10 seconds the experimenter retrieved the remaining four balls that had been withheld, showing them to infants before placing them out of sight under the table. A final 10-second measurement period – *8 Hidden, None Remaining* – followed. Each of the three measurement periods was presented twice. *8 Hidden, None Remaining* periods always followed *8 Hidden, 4 Remaining* periods, but otherwise order was counterbalanced.

Results and discussion

We predicted no difference in infants' searching across the different measurement periods when no objects were expected to remain in the box. This prediction was confirmed, both for the 2 Sets of 2 Block (searching on *2 Hidden, None Remaining* measurement periods did not differ from searching on *4 Hidden, None Remaining* measurement periods, $t(21) = -.83$, $p = .42$), and the 4 Sets of 2 Block (searching on *4 Hidden, None Remaining* measurement periods did not differ from searching on *8 Hidden, None Remaining* measurement periods, $t(21) = -.32$, $p = .76$). Therefore these scores were collapsed within each block.

Next we asked whether infants remembered the total number of objects hidden, searching longer when objects were expected to remain in the box than when the box was empty. In the 2 Sets of 2 Block, infants searched marginally longer in the *4 Hidden, 2 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = -1.91$, $p = .07$). However, in the 4 Sets of 2 Block infants searched equally in *8 Hidden, 4 Remaining* periods and in the collapsed *None Remaining* periods ($t(21) = -.86$, $p = .40$; Figure 1d).

Although infants' success at remembering two chunks of two objects each was only statistically marginal, the general performance pattern replicates that observed in other studies (Feigenson & Halberda, 2004, 2008; Experiment 1b). In contrast, we found no evidence that infants could remember eight total objects as four sets of two. When eight objects were hidden and only four retrieved, infants failed to continue searching.

Besides suggesting that infants failed to represent eight individual objects as four sets of two, Experiment 2 also shows that infants failed to use their approximate number representations. Six-month-old infants have been shown to use Approximate Number System (ANS) representations to discriminate approximate quantities in a 1:2 ratio (e.g. four vs. eight dots; Xu, 2003). However, infants in our task apparently failed to draw upon their ANS to motivate further searching after seeing eight balls hidden and retrieving just four. This concurs with previous findings that when infants track graspable, three-dimensional objects, they often activate individual object representations rather than approximate number representations (Cordes & Brannon, 2008; Feigenson & Carey, 2005; Feigenson, Carey & Hauser, 2002; vanMarle, 2012).

Infants in Experiments 1 and 1b failed to represent six objects as 'two chunks of three', or as 'exactly six'. Infants in Experiment 2 failed to represent eight objects either as 'four chunks of two', 'exactly eight', or 'approximately eight'. These failures set the stage for our central question: whether infants can represent larger numbers of individual objects by creating chunks out of chunks – that is, by adding another representational level to the remembered hierarchy. To test this, we next presented infants with the same eight identical balls as in Experiment 2. This time, we arranged the balls so as to encourage a third level of memory representation.

Experiment 3

To confirm that these infants could chunk objects, we again tested them in a 2 Sets of 2 Block like those of Experiment 1b and Experiment 2. This served as a comparison to the main test of interest: the 2 Superchunks Block. This was nearly identical to the 4 Sets of 2 Block from Experiment 2, except that rather than seeing eight objects arranged in an equi-spaced row in front of the box, infants saw them presented as one group of four to the box's right and another group of four to the box's left. Each group of four was further spatially subdivided into two sets of two. Our aim was to encourage infants to parse the array into three levels: the superchunk (left vs. right side of the box), the chunk (left vs. right platform on each side of the box), and the object (left vs. right ball on each platform).

Method

Participants

Twenty-two 13.5- to 15-month-old infants participated ($M = 14$ months, 2 days; 10 females). Six additional infants were excluded for failure to search (5) or parental interference (1).

Procedure

The ***2 Sets of 2 Block*** was identical to that of Experiment 2, except that the presentation platforms were aligned with the edge of the box rather than in front of it, approximately 10 cm further from infants than in Experiment 2.

The ***2 Superchunks Block*** was similar to the 4 Sets of 2 Block of Experiment 2 except that instead of appearing in an equi-spaced row in front of the box, the four presentation platforms were placed two to the right of the box and two to the left (Figure 1e). All other aspects of the stimuli, movements, and timing were as in the 4 Sets of 2 Block of Experiment 2.

Results and discussion

As before, we first asked whether infants' searching differed across the different *None Remaining* trials. We found that it did not, either for the 2 Sets of 2 Block (searching on *2 Hidden, None Remaining* trials did not differ from searching on *4 Hidden, None Remaining* trials, $t(21) = .81$, $p = .43$), or the 2 Superchunks block (searching on *4 Hidden, None Remaining* trials did not differ from searching on *8 Hidden, None Remaining trials*, $t(21) = .25$, $p = .81$). Therefore these scores were collapsed for each block.

Second, we asked whether infants remembered the total number of objects hidden, searching longer when objects were expected to remain in the box than when the box was empty. In the 2 Sets of 2 Block, infants searched longer in the *4 Hidden, 2 Remaining* periods than in the collapsed *None Remaining* periods, ($t(21) = -2.07$, $p = .05$). In addition, unlike in Experiment 2, infants in Experiment 3 searched longer in the *8 Hidden, 4 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = -2.49$, $p = .02$; Figure 1e).

Infants in Experiment 3 were provided with two levels of grouping cues: objects arranged to the left vs. right of the box, and each of these groups of four further spatially subdivided into two groups of two. In contrast, infants in Experiment 2 were provided only with one level of grouping cues: four groups of two objects each, arranged in an equi-spaced row. To compare infants' memory for the hidden objects when provided with two levels versus one level of grouping cues, we compared performance across Experiments 2 and 3. For the 2 Sets of 2 Blocks, infants' difference scores did not differ across the two experiments ($t(42) = .65$, $p = .52$). This, in combination with previous findings of infants successfully chunking four objects into two groups of two (Feigenson & Halberda, 2004, 2008; Experiment 1b), provides further evidence that infants can perform first-order chunking. It also assuages potential worries about the marginal significance of infants' success in the 2 Sets of 2 Block in Experiment 2. Across several different experiments in the present series and elsewhere, infants successfully represent two chunks of two.

More central to the present investigation is whether the additional grouping information in Experiment 3 helped infants to remember more objects, beyond their previously observed success with two chunks of two. We found that when presented with eight total objects, infants' difference scores were significantly greater in Experiment 3 (when eight objects were presented as two superchunks, each containing two chunks, each containing two objects) than in Experiment 2 (when eight objects were presented as four chunks, each containing two objects, $t(42) = -2.06$, $p = .045$).

Experiment 4

Previous work shows that in addition to spatiotemporal cues, featural and conceptual cues can drive infants' chunking (Feigenson & Halberda, 2008). In Experiment 4 we attempted to replicate the success of Experiment 3, this time asking whether infants can use a combination of spatiotemporal and featural/conceptual information to create three levels of memory representation. If so, this would bolster the claim that infants can organize object representations hierarchically in memory.

Method

Participants

Twenty-two 13.5- to 15-month-old infants participated (M = 14 months, 4 days; 10 females). Five additional infants were excluded for fussiness (1), failure to search (2), and experimenter error (2).

Stimuli

The stimuli were the yellow toy cats and red toy cars from Experiment 1b. Instead of four small presentation platforms, two longer (18 × 11.5 cm) platforms were used.

Procedure

The ***2 Sets of 2 Block*** was nearly identical to those in Experiments 2 and 3, except that toy cats and cars replaced the balls. On *2 Hidden, None Remaining* measurement periods infants saw one cat on one side of the box and one car on the other, then saw both objects hidden in the box. Infants were allowed to retrieve both objects, and subsequent searching was measured. On *4 Hidden, 2 Remaining* measurement periods infants saw two cats presented on one side of the box and two cars on the other. The experimenter hid all four objects in the box, but secretly withheld two of them out of reach in the back of the box. Infants were allowed to retrieve one cat and one car (sometimes with the experimenter's help, as in the previous experiments) before their searching was measured. On *4 Hidden, None Remaining* measurement periods the experimenter retrieved the remaining cat and car that had been withheld, and subsequent searching was measured. Side and order of object placement were counterbalanced.

In the ***2 Superchunks Block*** infants saw objects evenly spaced on the two platforms on either side of the box (Figure 1f). On *4 Hidden, None Remaining* measurement periods infants saw two cats presented on one platform and two cars on the other. Infants were allowed to retrieve all four objects (with the experimenter's help), then the experimenter placed the objects out of sight under the table and searching was measured. On *8 Hidden, 4 Remaining* measurement periods infants saw two cats and two cars presented on one platform (evenly spaced, identical objects adjacent) and two cats and two cars on the other. Unlike in Experiment 2 there were no spatiotemporal cues for subdividing the left and right side of these arrays. Instead, the conceptual and featural distinctions between the cats and cars provided a potential means for chunking the objects on each platform. The experimenter then hid all eight objects in the box, two at a time, and secretly withheld four of the eight out of reach at the back of the box. Infants were allowed to retrieve the four objects not being withheld (two cats and two cars). The experimenter then removed these and placed them out of sight under the table, and searching was measured. After 10 seconds the experimenter retrieved the four objects still remaining in the box, showed them to infants, and placed them under the table. A final 10-second measurement period followed: *8 Hidden, None Remaining*.

Results and discussion

We first asked whether infants' searching differed across the *None Remaining* trials. We found that it did not, either for the 2 Sets of 2 Block (searching on *2 Hidden, None Remaining* measurement periods did not differ from searching on *4 Hidden, None Remaining* measurement periods, $t(21) = .73$, $p = .47$), or the 4 vs. 8 block (searching on *4 Hidden, None Remaining* measurement periods did not differ from searching on *8 Hidden, None Remaining* measurement periods, $t(21) = .61$, $p = .55$). Therefore these scores were collapsed for each block.

Second, we asked whether infants remembered the total number of objects hidden, searching longer when more objects were expected to remain in the box than when the box was empty. In the 2 Sets of 2 Block, infants searched longer in the *4 Hidden, 2 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = -2.59$, $p = .02$). In the 2 Superchunks Block, infants also searched longer in the *8 Hidden, 4 Remaining* periods than in the collapsed *None Remaining* periods ($t(21) = -3.08$, $p = .01$; Figure 1f).

Finally, we compared infants' searching across experiments. We asked whether chunking cues aided infants' memory by comparing performance in Experiment 4 to that in Experiment 2. We found that for the 2 Sets of 2 Blocks, infants' difference scores did not differ between Experiments 4 and 2 ($t(42) = .46$, $p = .21$). In contrast, infants' performance diverged when presented with eight total objects, with infants searching longer for the missing objects only in Experiment 4 where superchunk information was provided ($t(42) = -2.35$, $p = .026$). Finally, we compared infants' searching across Experiments 3 and 4. Because both of these provided infants with superchunk information (differing only in the type of cue provided), we did not expect infants' difference scores to differ across the two experiments. This was confirmed, for both the 2 vs. 4 block ($t(42) = -.28$, $p = .43$), and the 4 vs. 8 block ($t(42) = .31$, $p = .20$).

These results replicate and extend those of Experiment 3, suggesting not only that infants can maintain three levels of memory representations, but also that they can use a combination of featural/conceptual and spatiotemporal information to do so.

General discussion

The present experiments offer insight into the limits and the flexibility of early chunking. First, they show that although first-order chunking is performed in infancy, it is highly constrained. Infants can bind representations of two individual objects into a chunk and maintain two such chunks in memory concurrently (Feigenson & Halberda, 2004, 2008; Experiments 1b, 3, and 4 in the present series). However, infants appear *unable* to bind three object representations into a chunk (Experiments 1 and 1b), even when given multiple redundant chunking cues. Furthermore, although infants can represent three two-object chunks at once (Feigenson & Halberda, 2008), infants cannot represent four two-object chunks (Experiment 2), at least at the age tested here and in the context of our task. Hence both the number of items that can occupy a chunk, and the number of chunks that can occupy a single level of representation, appear limited for infants, much as for adults (Chase & Ericsson, 1981; Cowan *et al*., 2004).

Building on these findings, our central question was whether infants can nest representations of chunks inside larger chunks. Our present results provide the first evidence that infants indeed can perform such second-order chunking, binding representations of individual objects into chunks, and then binding representations of chunks into superchunks. When presented with first-order chunking cues, infants in Experiments 1 and 1b failed to remember even a total of six hidden objects. But when provided with second-order cues that encouraged the binding of chunks into still larger chunks, infants succeeded in two experiments at remembering a total of eight hidden objects. This suggests that by maintaining three levels of representation – the individual object, the chunk, and the superchunk – infants can greatly exceed their typically observed WM limits.

Our results also bear on an alternative interpretation of previous work. Feigenson and Halberda (2004, 2008) found that infants could represent four objects only if these could be grouped into two sets of two. They interpreted this as demonstrating successful chunking by 14-month-olds. However, an alternative is that infants represented the arrays not in terms of chunks, but rather in terms of *pairs*. If infants have a basic concept PAIR, in addition to the basic concept OBJECT (Leslie & Chen, 2007), then they might have represented 'two pairs', rather than 'two chunks, each containing two objects'. Representations of pairs would not require hierarchical structuring in memory. The present studies are, on the one hand, consistent with Leslie and Chen's proposal that infants have a concept PAIR. We found that infants failed, in two experiments, to represent two chunks of three objects each, despite successfully representing three chunks of two objects each. However, our Experiments 3 and 4 show that infants must be representing the object arrays hierarchically, either by binding representations of individual objects into chunks, then binding representations of these chunks into superchunks, or by representing object PAIRS, then embedding further to create representations of 'pairs of pairs'. Further work will be needed to disentangle these possibilities, but we view the main contribution of these studies as showing that infants' memory can be structured hierarchically.

Another outstanding question is whether infants in Experiments 3 and 4 represented all eight objects individually in memory. Infants' success was indexed as continued searching after eight objects were hidden and only four of them retrieved – behavior consistent with representing eight as more than four, without necessarily representing the exact number of objects hidden. Several considerations are relevant to interpreting infants' success. First, as discussed earlier, ANS representations of 'about eight' did not appear to underlie infants' performance. The eight objects presented in Experiment 2 offered a stronger example of 'about eight' than did the eight objects in Experiments 3 and 4, because they occupied a single region in front of the box rather than two separate regions on either side. Yet infants failed in Experiment 2, suggesting that they did not represent 'about eight' objects in the box. Nor could infants in Experiments 3 and 4 have succeeded by forming two approximate number representations of 'about four' on each side of the box. Across many previous experiments, infants in the manual search task failed to represent a single set of four or more objects, either as individual objects or as an approximate cardinality (Barner *et al.*, 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2008). This suggests that ANS representations did not underlie infants' searching.

Instead, previous studies suggest that the task employed here activates individual object representations that support precise discriminations between arrays (Barner *et al.*, 2007; Feigenson & Carey, 2003, 2005; Feigenson & Halberda, 2004, 2008). For example, Rosenberg and Feigenson (in preparation) showed infants four identical objects arranged as two sets of two, all of which were then hidden in the box. After retrieving three of the four objects, infants continued searching for the one remaining object. The finding that infants represented the four objects precisely enough to discriminate their memory representation of the original array from an array containing just three objects suggests that representations of individuals are maintained during infants' chunking. However, future work should continue to examine the specificity of infants' chunked representations.

At present, our data suggest that 14-month-old infants can nearly triple their typically observed three-object WM capacity limit to represent at least eight objects. They do so by maintaining three concurrent levels of representation: the individual object, the chunk, and the superchunk. Further work will be needed to identify possible limits on the number of representational levels that infants can maintain. It also will be important to understand how the spontaneous hierarchical memory organization documented here in infants relates to the consciously controlled strategies used by older children and adults. For now, our findings add an important piece to the puzzle of memory development by implicating an aspect of memory organization used throughout the lifespan.

Acknowledgements

This research was supported by a James S. McDonnell Foundation Scholar Award and NSF R03 Grant HD054416 to LF. We are grateful to Andrea Stevenson, Yera Jeong, and Kirsten Schohl for assistance in data collection, and to the infants and parents of the Lab for Child Development for their participation. We thank Justin Halberda for suggestions for Experiment 2.

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Received: 15 December 2011
Accepted: 27 January 2013