

Conceptual knowledge increases infants' memory capacity

Lisa Feigenson* and Justin Halberda

Department of Psychological and Brain Sciences, The Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218

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Adults can expand their limited working memory capacity by using stored conceptual knowledge to chunk items into interrelated units. For example, adults are better at remembering the letter string PBSBCCNN after parsing it into three smaller units: the television acronyms PBS, BBC, and CNN. Is this chunking a learned strategy acquired through instruction? We explored the origins of this ability by asking whether untrained infants can use conceptual knowledge to increase memory. In the absence of any grouping cues, 14-month-old infants can track only three hidden objects at once, demonstrating the standard limit of working memory. In four experiments we show that infants can surpass this limit when given perceptual, conceptual, linguistic, or spatial cues to parse larger arrays into smaller units that are more efficiently stored in memory. This work offers evidence of memory expansion based on conceptual knowledge in untrained, preverbal subjects. Our findings demonstrate that without instruction, and in the absence of robust language, a fundamental memory computation is available throughout the lifespan, years before the development of explicit metamemorial strategies.

chunking | development | object | hierarchical

Working memory capacity is severely limited in adults (1–6) and infants (7–11), with both groups able to remember only about three separate items at once. One reason that adults are rarely conscious of this constraint is that we can hierarchically reorganize the to-be-remembered stimuli, thereby increasing the total number of items we can store. For example, the letter string PBSBCCNN is much easier to recall after recognizing the three familiar television acronyms PBS, BBC, and CNN that comprise it. This chunking entails the use of previously acquired concepts to parse an undivided array into smaller units that are more efficiently stored in memory. The stored representation now has two nested levels: the chunks (the television acronyms) and their components (the letters within each acronym).

Hierarchical memory reorganization is widely relied on by adults (12–17), both as an explicit strategy and as an unconscious memory process (14, 18, 19), but its origins remain a mystery. Five-year-old children can hierarchically structure memory if provided explicit instruction (20–22), raising the possibility that this process is a cultural construction acquired through explicit teaching. Infants have been shown to group items based on perceptual or statistical features (23–25), but such grouping does not truly expand item-based memory limits because it fails to preserve representations of the groups' individual components. And although infants exhibit greater memory capacity for spatially grouped than ungrouped items (26), this ability differs from classical chunking because it relies on external cues rather than internally stored knowledge. Therefore, it remains unknown how humans attain the ability to expand working memory based on previously acquired knowledge. Here, we tested whether this ability is learned through explicit instruction by examining the memory capacity of untrained infants.

Capacity limits on working memory have been demonstrated in adults in dozens of experiments using various methods. For example, adults shown briefly flashed arrays of letters and digits can only remember a limited number of items after the display

disappears (6). For several decades this limited number was thought to be 7 ± 2 (16). However, more recent analyses show that 7 ± 2 overestimates working memory capacity. When measures are taken to block chunking, adults can store only three to four items (1). This limit applies broadly to visual and auditory entities including colored shapes, oriented lines, spoken letters, and spoken words, for items presented either simultaneously or sequentially (for review, see ref. 1)[†].

Across several methodologies, infants, too, show an abrupt limit on the number of items they can simultaneously remember, regardless of whether items are presented sequentially or simultaneously (7–11). For example, infants between 10 and 20 months old remember and search for the correct number when one, two, or three objects are hidden in a box, but fail when four or more objects are hidden (7–9). Because objects are hidden for durations of several seconds or even tens of seconds, these tasks are thought to tap working memory limits rather than attentional limits. In the present experiments we asked whether infants can expand this limited-capacity memory by mentally reorganizing stimuli, much as adults can. We predicted that if memory expansion using stored conceptual knowledge needs no explicit training, then infants, like adults, will be able to exceed the three-item limit and remember four total objects, but only for arrays in which objects can be conceived of as forming meaningful conceptual groups. In adults, hierarchical reorganization is possible when stimulus items can be grouped based on conceptual, perceptual, or spatial cues (12–19). In the present studies we tested preverbal infants' ability to use each of these, focusing on the most abstract of the three: conceptual knowledge as a basis for memory reorganization.

Results and Discussion

In our experiments 14-month-old infants watched an experimenter hide objects in a box, and then were allowed to search for them. On some trials we hid four objects, allowed infants to retrieve two of them, then asked whether infants would continue searching for the remaining objects (which were secretly withheld). On other trials we hid two or four objects, allowed infants to retrieve all of them, and asked whether they would continue searching when the box was expected to be empty. If infants can successfully remember four objects they should search longer on trials when the box was expected to contain more objects than

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*To whom correspondence should be addressed. E-mail: feigenson@jhu.edu.

[†]Some authors have suggested that this limit originates even before items are stored in memory, when they are first attended (27). However, evidence for a three- to four-item limit of attention recently has been called into question (28), whereas evidence for a three- to four-item limit in working memory remains robust (1–6).

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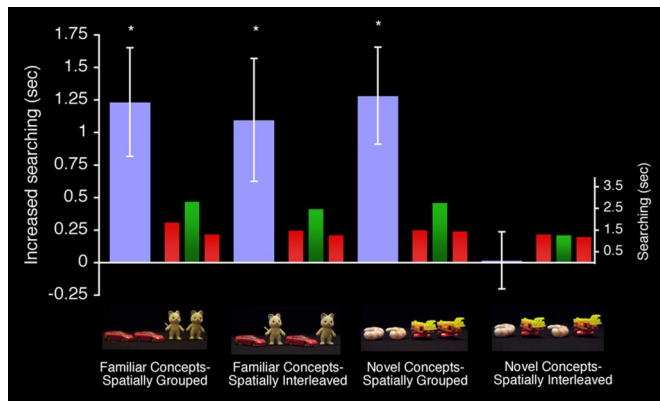


Fig. 1. The mean of increased searching (searching when the box contained more objects minus searching when the box was empty) (\pm SEM), average search times, and object configurations used in Exp. 1 are shown. The infants' average search times are plotted in triads on the right y axis. Each triad depicts mean searching when infants saw two objects hidden and had already retrieved two, infants saw four objects hidden and had already retrieved two, and infants saw four objects hidden and had already retrieved all four (reading left to right). Thus, for each condition increased searching (light blue bar) results from subtracting averaged searching on the two trials when the box was empty (red bars) from searching when the box was expected to contain more objects (green bar). The infants searched longer when more objects remained in the box than when the box was empty when presented with familiar objects, spatially grouped, familiar objects, spatially interleaved, and novel objects, spatially grouped. The infants did not search longer for objects remaining in the box when presented with novel objects, spatially interleaved.

when it was expected to be empty.[‡] Previous use of this method to measure infants' working memory reveals that infants succeed when one, two, or three objects are hidden, but consistently fail with four (7–9). Infants' searching in this method has been shown to depend solely on the number of objects remembered and not on infants' interest in object types (e.g., plain white balls versus small toys) (7), time delays between reaches (7, 26), age (between 10 and 20 months) (9, 29), or continuous variables such as total object area (7).

In our first experiment we compared 14-month-old infants' memory for four-object arrays that could be parsed based on conceptual or perceptual cues to arrays that could not. Infants ($n = 44$) saw toy objects that were either conceptually familiar (cats and cars) or novel (shrimps and tanks), as rated by parents. Objects were either spatially grouped or interleaved (Fig. 1). In contrast to the many previous experiments showing that infants fail to remember four total objects, we found that infants searched successfully when two sets of two conceptually familiar objects were presented (total = four objects), regardless of the objects' spatial organization. This success is most easily seen by subtracting infants' average searching on trials when the box was expected to be empty (i.e., after two objects had been hidden and both retrieved, and after four objects had been hidden and four retrieved[§]) from average searching on trials when the box was expected to contain more objects (i.e., after four objects had

[‡]We allowed infants to retrieve two of four rather than three of four objects before measuring their searching to provide a direct comparison with previous studies. In previous studies, the number of objects retrieved versus hidden was kept at a 1:2 ratio to control for the possibility that infants' failure to remember four was caused by an inability to discriminate a more difficult 3:4 ratio (30). Therefore, infants' previous failures show that upon viewing a four-object array, infants fail to represent exactly four objects, exactly three objects, or even more than two objects. Any success in the present experiments will not reveal which of these representations infants relied on. But critically, success would directly contrast with previous failures and show that arrays that can be mentally reorganized based on conceptual groups are better remembered than arrays that cannot.

[§]Throughout the experiments presented here and in previous work (7–9), searching that was measured after four objects had been hidden and four retrieved occurred after infants

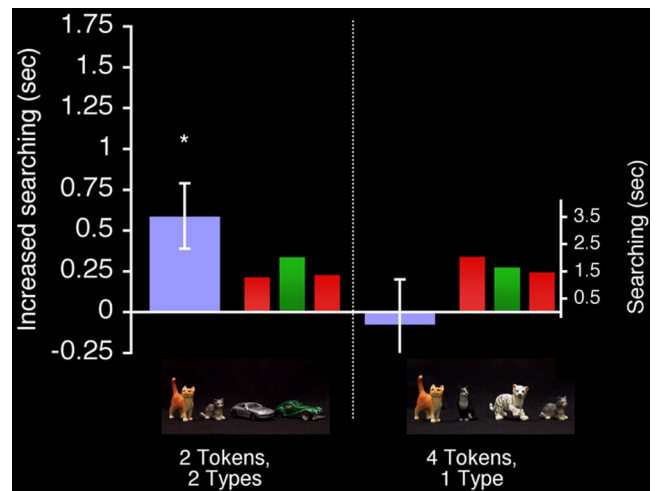


Fig. 2. The mean of increased searching (\pm SEM), average search times, and examples of the object configurations used in Exp. 2 are shown. The infants' average search times are plotted in triads on the right y axis. The infants showed increased searching when presented with two tokens of two different object types, but not when presented with four tokens of a single object type.

been hidden and only two retrieved). When infants saw two cats and two cars hidden and had retrieved one cat and one car, this measure of “increased searching” was significantly greater than zero [familiar concepts spatially grouped: $t(21) = 2.95$, $P = 0.008$; familiar concepts spatially interleaved: $t(21) = 2.32$, $P = 0.030$]. However, when infants saw two shrimp and two tanks hidden and had retrieved one shrimp and one tank, infants only showed significant increased searching when the objects within each set were directly adjacent to one another [novel concepts spatially grouped: $t(21) = 3.44$, $P = 0.002$; novel concepts spatially interleaved: $t(21) = 0.08$, $P = 0.94$] (Fig. 1). These results suggest that infants' memory for conceptually familiar objects was hierarchically reorganized regardless of the objects' spatial arrangement, but that their memory for conceptually novel objects was only hierarchically reorganized when identical objects were adjacent and formed a perceptual Gestalt. This pattern of success and failure, combined with all of infants' previous failures to remember four objects, reveals that infants remembered a greater number of objects when arrays could be parsed into smaller units on the basis of conceptual or perceptual information.

How abstract is the underlying conceptual knowledge supporting infants' hierarchical memory reorganization? If infants use abstract categories to structure memory (e.g., if they parse the array based on the concepts CAT and CAR), then they should also succeed with nonidentical tokens of the same conceptual category. To ask whether infants can mentally group nonidentical category members we tested a separate group of infants ($n = 22$) on a within-subjects comparison involving two conditions, with order counterbalanced (Fig. 2). In the two tokens, two types condition infants saw four nonidentical objects from two familiar categories (e.g., an upright orange cat and a reclining black cat; a gray sports coupe and a green station wagon). As in Exp. 1, the question was whether infants would continue searching after seeing these four objects hidden and retrieving just two of them. Infants succeeded, demonstrating significant increased searching after seeing two nonidentical cats and two nonidentical cars hidden and retrieving just one cat and one car [$t(21) = 2.99$, $P = 0.007$]. In the four tokens, one type condition these same infants saw arrays of four nonidentical cats or four

had retrieved the first and second objects from the box, and the experimenter had retrieved the third and fourth and shown them to infants (see *Methods*).

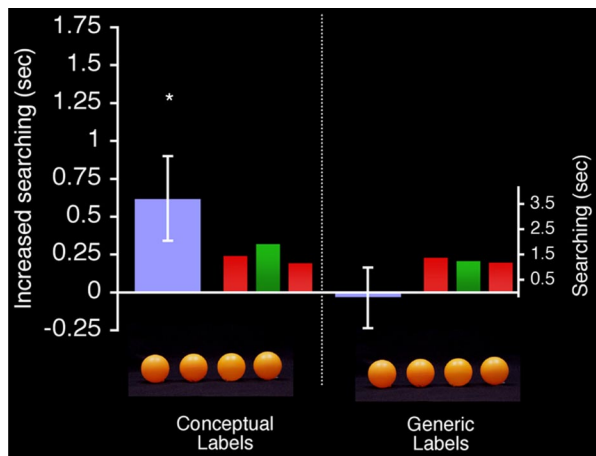


Fig. 3. The mean of increased searching (\pm SEM), average search times, and object configurations used in Exp. 3 are shown. The infants' average search times are plotted in triads on the right y axis. The infants showed increased searching when presented with conceptual labels ("dax, dax, blicket, blicket"), but not when presented with generic labels ("this, this, that, that").

nonidentical cars. Because all of the objects were from the same conceptual category, there was no clear basis for parsing the array. We found that infants failed to show increased searching in the four tokens, one type condition [$t(21) = -0.38, P = 0.71$], consistent with infants' previous failures to remember four objects in the absence of cues for hierarchical reorganization.

These findings suggest that conceptual knowledge increased infants' memory. However, an alternative explanation is that some of our arrays supported perceptual grouping, whereas others did not, and that only perceptual cues supported chunking (i.e., no conceptual knowledge was required). Infants in our first experiment likely had more previous experience with cats and cars than with shrimps and tanks, perhaps making it easier to form groups based on familiar perceptual features. And although Exp. 2 showed that infants succeed with nonidentical tokens, it does not rule out perceptual grouping because two different cats are more perceptually similar than a cat and a car. We therefore tested a third group of infants ($n = 22$) in two conditions each, with order counterbalanced. As in Exps. 1 and 2 we compared infants' searching after seeing four objects hidden and retrieving just two of them to their searching after seeing two objects hidden and retrieving two, or after seeing four hidden and retrieving four. Crucially, in Exp. 3 arrays always contained identical equi-spaced orange balls (Fig. 3). In previous work, infants always fail with such arrays (7–9). However, in this experiment we made perceptually identical objects conceptually distinct through verbal labeling. Before hiding, the experimenter pointed to each ball in turn and, in the conceptual labels condition, said, "Look, a dax! Look, a dax! Look, a blicket! Look, a blicket!" In the generic labels condition she said, "Look at this! Look at this! Look at that! Look at that!" Previous studies show that infants treat objects referred to with the same count noun (but not the same generic label) as members of the same category (31). Thus both conditions involved perceptually ungrouped arrays, but only the conceptual labels condition provided verbal evidence that objects were members of distinct categories [consistent with them sharing a hidden property or essence (32,33)]. As predicted, infants showed significant increased searching in the conceptual labels condition [$t(21) = 2.21, P = 0.039$] but not in the generic labels condition [$t(21) = -0.18, P = 0.86$] (Fig. 3), suggesting that infants grouped objects based on shared linguistic labels. There was no effect of whether infants were tested in the conceptual labels or the generic labels condition

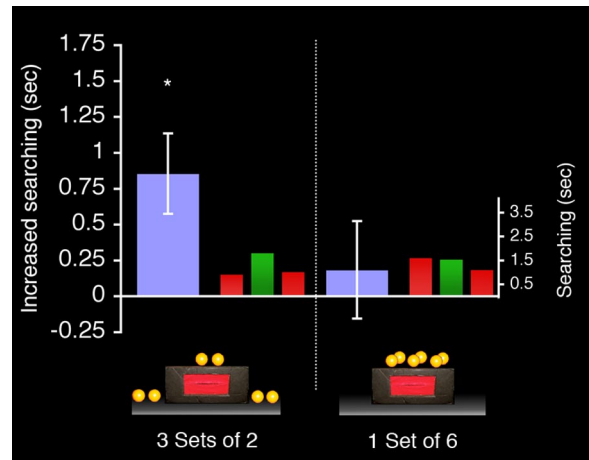


Fig. 4. The mean of increased searching (\pm SEM), average search times, and object configurations used in Exp. 4 are shown. The infants' average search times are plotted in triads on the right y axis. The infants showed increased searching when presented with six objects as three sets of two, but not when presented as a single set of six.

first. Hence, hearing contrasting count nouns in the conceptual labels trials did not lead infants to treat balls as forming two sets on all subsequent trials; rather, the effect of grouping seemed limited to objects that had been given contrasting labels immediately before hiding. Overall, infants' successful search pattern in the conceptual labels condition shows that working memory can be expanded via conceptual cues to hierarchical reorganization, even in the absence of any visual basis for parsing the stimulus array.

Finally, hierarchical memory reorganization is a powerful tool for adults because rather than merely enabling the storage in memory of an extra item or two, it enables the storage of items far exceeding the usual three- or four-item working memory limit (14). To ask whether infants can robustly increase capacity in this way we tested a separate group of infants ($n = 22$) on a within-subjects comparison involving two conditions, with order counterbalanced (Fig. 4). In the three sets of two condition, six identical orange balls were presented spatially grouped such that two balls were placed on a platform to the left of the box, two were placed atop the box, and two were placed on a platform to the right of the box. This arrangement provides spatial grouping cues (26) for dividing six identical balls into three sets of two. In the one set of six condition, all six balls were placed in a single set atop the box, providing no cues to grouping (26). In each condition, we compared infants' searching when the box was expected to contain more objects (i.e., after six objects had been hidden and four were retrieved) versus when the box was expected to be empty (i.e., after four objects had been hidden and four retrieved, and after six had been hidden and six retrieved).[†] We found that infants showed significant increased searching in the three sets of two condition [$t(21) = 3.02, P = 0.006$], but not in the one set of six condition [$t(21) = 0.55, P = 0.589$] (Fig. 4), suggesting that infants successfully differentiated the hiding of six from the hiding of four objects when spatial grouping cues were present, but not when they were absent. The finding that infants experience memory expansion with arrays of six items, double the number of items possible given their typical

[†]On four object trials in both conditions, balls were always presented as two sets of two with two on the left platform and two on the right platform. On every trial, infants were allowed to retrieve two balls from the box and the experimenter then retrieved the remaining two or four balls, depending on the trial type, and showed them to infants.

three-item capacity, further aligns the abilities of untrained 14-month-olds with those of adults.

These experiments provide evidence that, without training and in the likely absence of conscious effort, infants can use multiple sources of information, including stored conceptual knowledge, to increase the number of items they can remember. This knowledge allows infants to identify smaller groups within a larger collection, even among perceptually identical items. Mentally organizing items in this way provides a more efficient format for structuring memory, resulting in greater storage capacity.

Our results suggest that the restructuring of memory is a fundamental and early-developing solution to the problem of storing large amounts of information in a limited-capacity system. Previous work has found that infants use spatial, perceptual, and conceptual information to segregate objects from ambiguous scenes (34, 35). For example, 4.5-month-old infants parse an array containing a yellow cylinder abutting a blue cube into two distinct objects (34). The present work shows that infants use this ability not only to parse complex scenes into their component objects, but also to conceive of individual objects as forming unified groups. This grouping expands infants' working memory capacity while still preserving representations of the individual component items. This hierarchical restructuring offers a way of expanding memory storage beyond the strict constraints of an item-based working memory.

Are the memory processes uncovered in the present experiments the same processes that underlie classical chunking in adults? The answer to this question depends on the definition of chunking. On some readings, chunking requires conceptual recoding of the type involved when parsing PBSBBCNN into PBS, BBC, and CNN. Such recoding entails that each of the newly created representational units corresponds to an existing, unitary concept in long-term memory (e.g., CNN is the media corporation that employs Wolf Blitzer) (36, 37). A different definition of chunking also requires conceptual knowledge, but does not require recoding. For example, it is easier for adults to remember "eggplant, screwdriver, carrot, artichoke, hammer, pliers" than to remember "eggplant, broccoli, carrot, artichoke, cucumber, zucchini" because it is easier to remember three tokens of two conceptual types than six tokens of one type (38). In this case, unlike in the example of the unified concept CNN, memory expansion occurs even though there is no existing unified concept "eggplant-carrot-artichoke" that contains all and only these three items. A third definition of chunking requires no conceptual knowledge at all, but rather allows nonconceptual information such as perceptual or spatiotemporal similarity to serve as a basis for parsing the array (1). An example is the everyday practice of dividing phone, credit card, and social security numbers into groups of two to four digits based on the digits' temporal or spatial proximity. Importantly, it is not just the number of groups that is remembered, but also the identity of the groups' components, demonstrating the hierarchical nature of the representations involved. The differences between these three definitions highlight the lack of consensus as to what constitutes chunking. However, the above views all agree that memory expansion depends on hierarchical restructuring. The present experiments show that preverbal infant memory spontaneously engages in this process.

Several avenues for further inquiry present themselves. First, psychology and cognitive science still lack a compelling mechanistic account of how hierarchical reorganization can expand working memory. The proposal of such an algorithm is beyond the scope of the present work. However, our demonstration that multiple sources of evidence (conceptual, perceptual, linguistic, and spatial) can each motivate memory expansion in untrained infants will help constrain the problem space and provide data that will be valuable in evaluating any future algorithmic pro-

posals. Second, the result that 14-month-old infants can use hierarchical reorganization to expand memory, whereas much older, preschool-aged children often need explicit instruction to do so (20–22), suggests that the voluntary control of memory reorganization likely undergoes significant developmental change. Future work will be needed to understand shifts in the endogenous versus exogenous control of memory reorganization. Third, limits on early abilities should be explored. Adults have been shown to consciously create elaborate mental hierarchies in which dozens of items can be held in memory (14). It remains unknown whether infants can also do so, or how the parametric limits on memory reorganization might change with development. Finally, our results raise the question of what format and quantity of knowledge are required to support this process. The 14-month-old infants we tested had the opportunity for everyday experience with some of our stimulus types (cats, cars) and were better at remembering these than novel types (shrimps, tanks). Eighty-six percent of infants in Exp. 1 were also reported by parents to know at least one of the words "cat" and "car," consistent with published vocabulary development norms (39). This linguistic knowledge may have provided a basis for chunking. However, Exp. 3 shows that infants did not require much prior experience with particular object names to expand memory. It is therefore likely that there are several possible routes to the hierarchical expansion of memory, including nonlinguistic conceptual knowledge, perceptual experience, and linguistic knowledge. Future research may reveal distinct developmental trajectories for each of these cues. At present, our results show that each of these cues supports the expansion of working memory capacity by the age of 14 months.

Methods

In Exp. 1, 22 infants participated in the familiar concepts–spatially grouped and the novel concepts–spatially interleaved conditions (mean age 14 months, 6 days) and 22 infants participated in the familiar concepts–spatially interleaved and the novel concepts–spatially grouped conditions (mean age 14 months, 10 days). All 22 infants in Exp. 2 participated in both the two tokens, two types and the four tokens, one type conditions (mean age 14 months, 3 days). All 22 infants in Exp. 3 participated in both the conceptual labels and the generic labels conditions (mean age: 14 months, 14 days). All 22 infants in Exp. 4 participated in both the three sets of two and the one set of six conditions (mean age: 14 months, 5 days). Condition order was counterbalanced.

Each infant completed four trials of each of the following three types, with the exception of infants in Exp. 4 (see below). At the beginning of four objects hidden, two retrieved trials the experimenter introduced the empty box, placed four equi-spaced objects atop it for 6 s total, then inserted them. She allowed infants to retrieve two objects (the other two were secretly withheld via a concealed opening in the back of the box) and to hold them for 5 s before taking them away. A 10-s measurement period followed during which the experimenter lowered her head to avoid cuing infants, and any searching for the missing objects was recorded. After 10 s had passed infants saw the experimenter retrieve the missing objects through the front of the box, consistent with them having been simply out of reach. Another 10-s measurement period followed, constituting the four objects hidden, four retrieved trial. Afterward the experimenter removed the box from the table before starting the next trial. In two objects hidden, two retrieved trials the experimenter introduced the empty box, placed two objects atop it for 6 s, inserted them, and allowed the infant to retrieve both. After 5 s she took both objects away, lowered her head, and a 10-s measurement period followed. Order of trial type was counterbalanced within each experiment, except that four objects hidden, four retrieved trials always immediately followed four objects hidden, two retrieved trials.

The design of Exp. 4 was identical, except that in six objects hidden, four retrieved trials the experimenter introduced the empty box, placed two balls on a small platform to the box's left, placed two balls atop the box, then placed two balls on a platform to the box's right. The balls were visible for \approx 8 s, then were inserted into the box. Infants were then allowed to retrieve two objects and the experimenter quickly retrieved two more and showed them to the infants before taking all four of the retrieved balls away. A 10-s measurement period followed during which the experimenter secretly withheld the two remaining objects. After 10 s had passed infants saw the experimenter retrieve the missing objects through the front of the box, consistent with them having

been simply out of reach. Another 10-s measurement period followed, constituting the six objects hidden, six retrieved trial. Afterward, the experimenter removed the box from the table before starting the next trial. In four objects hidden, four retrieved trials the experimenter introduced the empty box, placed two balls on the left platform and two balls on the right platform, then inserted all four balls into the box. The infants were allowed to retrieve two balls and the experimenter quickly retrieved the other two and showed them to the infants before taking all four of the retrieved balls away. A 10-s measurement period followed. In all other ways, the manner of presentation was identical to that in Exps. 1–3.

Searching was coded from video by two naive observers whose frame-by-frame agreement averaged 92% across all trials. To qualify as searching, one of the infants' hands had to be inserted through the box's opening at least up to the second knuckle. Increased searching was computed by averaging the two trial types in which the box was empty (two objects hidden, two retrieved and four objects hidden, four retrieved or four objects hidden, four retrieved and six objects hidden, six retrieved), which did not statistically differ, and subtracting this from searching when the box contained more objects (four objects hidden, two retrieved or six objects hidden, four retrieved). In these and other experiments using this method (7–9), infants searched for short durations even on trials when the box was expected to be empty. This baseline level of searching likely resulted from our intentional exclusion of other

stimuli or social interaction during the critical measurement periods and from the infants' intrinsic enjoyment in reaching into the box. Critically, however, in trials on which the infants could hierarchically reorganize the array based on conceptual, perceptual, linguistic, or spatial cues, the duration of searching observed when more objects remained in the box (i.e., when four objects were hidden and only two had been retrieved or when six objects were hidden and only four had been retrieved) represented a ≈ 40 –50% increase over this baseline level of searching. This significant increase indicates that infants successfully remembered the hidden items.

To ensure that the experimenter did not inadvertently cue infants, eight observers blind to trial type watched only the measurement periods from 50% of all trials and guessed whether more objects remained in the box by watching the experimenter's face and hands. They averaged 51% correct (chance = 50%).

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