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Memory load affects object individuation in 18-month-old infants

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ABSTRACT

Accurate representation of a changing environment requires individuation—the ability to determine how many numerically distinct objects are present in a scene. Much research has characterized early individuation abilities by identifying which object features infants can use to individuate throughout development. However, despite the fact that without memory featural individuation would be impossible, little is known about how memory constrains object individuation. Here, we investigated infants' ability to individuate multiple objects at once and asked whether individuation performance changes as a function of memory load. In three experiments, 18-month-old infants saw one, two, or three objects hidden and always saw the correct number of objects retrieved. On some trials, one or more of these objects surreptitiously switched identity prior to retrieval. We asked whether infants would use this identity mismatch to individuate and, hence, continue searching for the missing object(s). We found that infants were less likely to individuate objects as memory load grew, but that infants individuated more successfully when the featural contrast between the hidden and retrieved objects increased. These results suggest that remembering more objects may result in a loss of representational precision, thereby decreasing the likelihood of successful individuation. We close by discussing possible links between our results and findings from adult working memory.

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Introduction

To learn about and act on the surrounding world, infants must represent information under conditions of noisy input. Objects frequently become occluded by surfaces or by other objects, necessitating the ability to remember items that are outside of immediate perception. Within the first few months of life, infants have made headway in solving this problem, continuing to represent objects that are hidden by other objects or obscured by darkness (e.g., Baillargeon, Spelke, & Wasserman, 1985; Clifton, Perris, & McCall, 1999; Shinskey & Munakata, 2003; Spelke, Breinlinger, Macomber, & Jacobson, 1992). However, even the briefest loss of perceptual contact introduces an important ambiguity: Is an object seen at Time 2 the same object seen at Time 1, or is it instead a new object? This *individuation* problem serves as a case study for understanding how observers coordinate different pieces of information in memory.

Much recent work has helped to characterize early individuation abilities. This work has revealed that from early in infancy, infants can use spatiotemporal information to determine the number of objects in a scene (Krojgaard, 2007; Xu & Carey, 1996). For example, Spelke and colleagues showed 4-month-old infants two spatially separated screens. An object emerged from behind one screen and then disappeared again. An identical object emerged from behind the other screen and then disappeared without any object appearing in the gap between the screens. Despite never having seen more than one object at a time, infants looked longer when the screens lifted to reveal just one object than when they lifted to reveal two objects, suggesting that infants successfully used the objects' spatiotemporal histories to decide that two distinct objects must be present (Spelke, Kestenbaum, Simons, & Wein, 1995).

When spatiotemporal information does not disambiguate a scene, infants also can individuate using featural information. For example, Xu and Carey (1996) showed infants a duck emerging from and then disappearing behind one edge of a single screen. A truck then emerged from and disappeared behind the other edge of the screen. Twelve-month old infants, but not 10-month old infants, successfully used the contrast 12-month-olds, but not 10-month-olds, successfully used the contrast between these successive object viewings to infer the presence of two objects, looking longer when the screen lifted to reveal just a single object relative to their baseline preference. For these older infants, some additional evidence suggests that infants used the featural differences between objects to set up contrasting kind representations and that these kind representations are critical to individuation (Bonatti, Frot, Zangl, & Mehler, 2002; Xu, Carey, & Quint, 2004; Xu, Cote, & Baker, 2005). However, when the task is made simpler (e.g., Wilcox & Baillargeon, 1998b; Wilcox & Chapa, 2002; Wilcox & Schweinle, 2002) or when given additional experience with objects' features (Wilcox, Woods, & Chapa, 2008; Wilcox, Woods, Chapa, & McCurry, 2007), infants much younger than 12 months also appear to use featural cues to individuate and can do so with objects that do not clearly contrast in kind membership (e.g., ball vs. box). Taken together, these studies of infants' object individuation abilities have revealed which object features infants can use for individuation as well as which experimental paradigms make individuation more or less difficult (e.g., Bonatti et al., 2002; Krojgaard, 2007; Surian & Caldi, 2010; Wilcox & Baillargeon, 1998a, 1998b; Xu et al., 2005).

Whether based on spatiotemporal or featural information, individuation requires memory. For example, when individuating using featural information, infants must remember the features of the object that disappeared at Time 1 (yellow, duck-shaped), compare these to the features of the object that emerged at Time 2 (red, truck-shaped), and decide whether these viewings were consistent with the presence of just a single object. Without remembering the first object, infants would have no basis for comparison and, hence, would fail to individuate. Yet, little research has addressed the question of how memory constrains early individuation abilities. For working memory, abundant evidence suggests that the number of objects that can be concurrently represented is limited, with both adults (for reviews, see Cowan, 2005; Drew & Vogel, 2009) and infants (for reviews, see Feigenson, 2011; Feigenson, Dehaene, & Spelke, 2004) limited to remembering three or four items at once. Additional work suggests that even when operating within these capacity limits, remembering larger numbers of items may come at a cost; several studies have found that memory precision for an object's features may decline as a function of the number of objects being remembered (Alvarez & Cavanagh, 2004; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; Wilken & Ma, 2004; Xu & Chun, 2006).

The evidence that working memory can maintain multiple object representations at once, and that representational resolution may interact with memory load, motivates several questions regarding infants' individuation abilities. First, how many objects are infants able to individuate? Nearly all extant studies of early individuation abilities asked whether infants can infer the presence of a single additional object in a scene. In these studies, infants saw just one object at a time (e.g., a duck at Time 1 and then a truck at Time 2). Successful individuation shows that infants were able to maintain one object representation in memory and compare this with a second visible object. However, given evidence that infants can remember the features of multiple objects at once (e.g., Kaldy & Leslie, 2003; Rose, Feldman, & Jankowski, 2001; Ross-Sheehy, Oakes, & Luck, 2003), infants also may be able to make *multiple* comparisons over several object representations being maintained concurrently in memory and, thereby, individuate more than one object at a time. An example of this would be an infant who sees her mother put a cracker and a grape in a bowl and then reaches into the bowl to retrieve a Cheerio and a banana. Does this infant, who has retrieved the expected number of objects, detect the mismatch in object identity such that she still expects a cracker and a grape to remain in the bowl?

Several studies have asked whether infants can remember and re-identify multiple objects at once given brief exposure to a scene (e.g., Kaldy & Leslie, 2003). However, in these studies, spatiotemporal information unambiguously specified the number of objects present such that infants did not need to use featural information to decide how many objects were in the scene (for further discussion of the distinction between object individuation and object identification, see Tremoulet, Leslie, & Hall, 2000). To our knowledge, only one existing study bears on the question of whether infants use featural information to individuate multiple objects at once. Leslie and Chen (2007) showed 11-month-olds pairs of objects emerging from and then disappearing behind a screen. Either infants saw a pair of circles emerge and then disappear, followed by a pair of triangles (an XX/YY sequence), or they saw a pair containing one circle and one triangle emerge and then disappear twice (an XY/XY sequence). When the screen was then lifted to reveal just a single circle and a single triangle, infants in the matched pairs (XX/YY) condition looked longer than infants in the mismatched pairs (XY/XY) condition. This might suggest that infants in the XX/YY condition used a combination of spatiotemporal and featural cues to establish representations of two distinct pairs (four total objects) and, therefore, looked longer when just two objects were revealed. Alternatively, infants might have expected to see an array containing objects that were identical rather than contrasting. Therefore, it remains unknown whether infants can use features to determine the number of objects present when shown more than one object at a time.

A second open question motivated by studies of working memory is whether infants' ability to use featural information as a basis for individuation is affected by the number of objects being remembered. If there is a trade-off between memory load and the featural resolution of the representations (Alvarez & Cavanagh, 2004), then remembering more objects may decrease featural resolution enough to make individuation impossible. That is, when remembering just a single object, infants may be able to use a particular featural contrast in order to individuate, but when remembering multiple objects, infants may fail to use this very same featural contrast. Previous work suggests that within the domain of long-term memory, increasing memory load causes a decline in infants' memory for relations among objects and their features (Bhatt & Rovee-Collier, 1997). However, no such evidence exists for infants' working memory or for early individuation abilities.

Here, we aimed to address these open questions, asking whether infants can individuate when presented with more than one object at a time and whether infants' ability to individuate changes as a function of the number of objects being remembered. We used a variation of the manual search task that has been shown to measure infants' memory for hidden objects (Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005) and that previously has been used to study infants' individuation abilities (Van de Walle, Carey, & Prevor, 2000; Xu et al., 2005). Infants saw one, two, or three toys presented side by side and then hidden in a box. Next, infants were allowed to retrieve the same number of items just hidden; for example, if two objects were hidden, then two were always retrieved. On some trials, the retrieved items were exactly those that infants had just seen hidden. On other trials, one or more of the objects surreptitiously switched identity. Previous studies have shown that 14-month-olds always search for the correct *number* of items when up to three objects are hidden

(Feigenson & Carey, 2003, 2005). Therefore, the infants we tested here were also expected to remember the correct number of items. Our new question was whether infants would also remember the items' *features* and whether this would vary as a function of the number of items hidden. If infants correctly remember the items' features and detect the identity switch, they should search longer for the missing item(s) on trials when a retrieved item(s) has been switched than when no switch has occurred.

We tested 18-month-olds for two reasons. First, the working memory capacity of infants around this age has been well documented for both simple objects (Barner et al., 2007; Feigenson & Carey, 2003, 2005) and complex objects (Feigenson & Halberda, 2008). In both cases, infants successfully remember the presence of three hidden objects, providing empirical support for our assumption that infants would always remember the correct *number* of hidden objects for all of the array sizes we tested. However, no study has asked whether infants also remember the objects' features—a question we sought to answer here. Second, it has previously been shown that infants ranging from 12 to 18 months of age successfully use object features to individuate when just a single object has been hidden, continuing to manually search after seeing one object hidden and finding a different object (Lecompte & Gratch, 1972; Van de Walle et al., 2000).

In Experiment 1, we measured infants' individuation abilities when one, two, or three objects had been hidden and exactly those same objects were retrieved versus when one of the objects had unexpectedly switched into a different object. In Experiment 2, we tested infants using the same design as in Experiment 1, but this time heightening the featural difference between what was hidden and what was retrieved. We again hid either one, two, or three objects, and either those same objects were retrieved or one of the objects had unexpectedly changed into a nonsolid substance—a change that previous research suggested would be particularly salient to infants. Finally, in Experiment 3, we hid one, two, or three objects and compared infants' individuation abilities when exactly those same objects were retrieved versus when *all* of the objects switched identity.

Experiment 1

Method

Participants

The participants were 16 infants (9 girls and 7 boys, mean age = 18 months 23 days, range = 18 months 7 days to 19 months 12 days). An additional 2 infants were excluded for fussiness. Infants were recruited by mail and by telephone, as approved by the Johns Hopkins institutional review board. At the end of the session, infants received a small gift (a book, a T-shirt, or a toy) to thank them for participating.

Materials

Infants retrieved objects from a $32 \times 25 \times 12.5$-cm black box with a spandex-covered opening in its front face. The spandex had a horizontal slit through which infants could reach but not see. The box had a concealed door in its back face through which the experimenter could surreptitiously insert or remove objects.

Previous research has shown that infants can use a variety of features to individuate, including shape, size, texture, luminance, color, and kind membership (Bonatti et al., 2002; Wilcox, 1999; Woods & Wilcox, 2006; Xu et al., 2004). Because we wanted to ensure that any observed failure of individuation would not be due to the particular object features we used, we selected objects that differed in many different features, including color, shape, texture, and category membership. The stimuli were small toys like those that infants encounter in everyday play ($\sim 7 \times 5$ cm): a fuzzy white cat, a red fabric shoe, and a yellow metal bus. On some trials, infants retrieved exactly these same objects; on other trials, they retrieved one switched object (e.g., a red metal car instead of the fuzzy white cat) plus the other objects that had originally been hidden (e.g., the red fabric shoe and yellow metal bus) (see Table 1).

Table 1
Experimental design for Experiments 1 to 3.

	One-object memory load		Two-object memory load		Three-object memory load	
	No Switch	Switch	No Switch	Switch	No Switch	Switch
All experiments: Objects hidden	CAT		CAT SHOE		CAT SHOE BUS	
Experiment 1: Objects retrieved	cat	**car**	cat shoe	**car** shoe	cat shoe bus	**car** shoe bus
Experiment 2: Objects retrieved	cat	**substance**[a]	cat shoe	**substance**[a] shoe	cat shoe bus	**substance**[a] shoe bus
Experiment 3: Objects retrieved	cat	**car**	cat shoe	**car duck**	cat shoe bus	**car duck brush**

[a] The substance retrieved on Switch trials in Experiment 2 was a nonsolid substance made of gelatinous orange plastic. The substance lacked stable boundaries or a rigid shape and was easily deformable by grasping.

Design and procedure

Infants first were familiarized to the experimental procedure by watching the experimenter insert a set of toy keys through the spandex-covered opening in the front of the box. After infants had successfully retrieved the keys at least once, the six critical trials began.

On each critical trial, the experimenter placed one, two, or three objects atop the box using a single hand motion. She pointed to each object in turn (taking 3 s per object)[1] and said, "Look at that. See that?" She then picked up the entire array in one hand and inserted it through the front face of the box. Immediately afterward, infants were allowed to reach through the spandex and retrieve one of the objects from the box, and the experimenter immediately retrieved any remaining objects and gave them to the infants. This was done in order to equate the time elapsed between the hiding of the object(s) and the start of the measurement period across the three different memory loads. That is, because the measurement period did not start until infants had seen the same number of objects retrieved from the box as they had seen hidden, allowing infants to sequentially retrieve each hidden object from the box would have confounded memory load (the number of objects being remembered) with retention interval (the time elapsed between object hiding and the start of the measurement period). Infants were allowed to examine the retrieved objects for a total of approximately 3 s before the experimenter took all of the objects away (leaving the box in place), and the 10-s measurement period began. At this point, the number of objects that had been retrieved from the box matched the number of objects that had been hidden, and the question was whether infants expected any further objects inside the box.

On half of the trials, all of the retrieved objects were exactly those that had just been hidden (No Switch trials). For example, on a three-object No Switch trial, infants saw a cat, a shoe, and a bus hidden and then saw a cat, a shoe, and a bus retrieved. On the other half of the trials, one of the retrieved objects had changed identity across superordinate kinds (Switch trials). For example, on a three-object Switch trial, infants saw a cat, a shoe, and a bus hidden and then saw a car, a shoe, and a bus retrieved (see Table 1). The switch in object identity was accomplished by having the experimenter secretly preload the box with the "switch" object before the start of the trial out of infants' sight. The experimenter then placed the box on the table, and infants watched as she presented and then inserted the target object(s) (e.g., cat, shoe, bus). As she inserted the object(s), the experimenter surreptitiously used her other hand to reach through the concealed door in the back of the box, grasp one of the target objects (e.g., cat), and remove it from the back of the box, leaving only the pre-loaded switch object (e.g., car) plus, on two- and three-object trials, the remaining target object(s) (e.g., shoe and bus). On Switch trials, the experimenter placed the switch object at the very front of the box's opening such that infants always retrieved the switch object first. The object that switched identity was constant for each infant in order to reduce potential confusion at seeing different changing objects across trials, but it was counterbalanced across infants.

[1] We selected this exposure time in order to allow infants ample time to encode the objects into memory. Infants considerably younger than those we tested here (10-month-olds) successfully remember the features of up to three simple items when given shorter exposure times (500 ms: Ross-Sheehy et al., 2003; 3 s: Rose et al., 2001).

The dependent measure was the total amount of time infants searched the box during each 10-s measurement period. Searching was defined as a reach through the front face of the box with either hand, with infants' fingers inserted through the box's opening at least up to their second knuckle (for details, see Feigenson & Carey, 2003). During the measurement period, the experimenter lowered her head and closed her eyes to avoid cueing infants. After the 10-s measurement period ended, she said, "Good job" and removed the box from the table. If infants were actively searching at the moment when 10 s had passed, they were counted as searching until their hand(s) had been withdrawn from the box.

On Switch trials, the object that had originally been hidden (and had surreptitiously been replaced with a different object) was never retrieved after the measurement period had ended (by either infants or the experimenter). This avoided the possibility of teaching infants that on some trials, but not on others, further objects remained in the box. Importantly, this was constant regardless of the number of objects in the hiding array. Therefore, if we found that on Switch trials infants searched differently depending on the number of objects that had been hidden, this cannot be attributed to receiving feedback (because no objects were ever retrieved after a measurement period began).

Infants were tested with three memory loads (one, two, or three hidden objects), with memory load order (ascending or descending) counterbalanced across infants. Each memory load involved one No Switch trial and one Switch trial; which one came first was counterbalanced across infants. Thus, each infant participated in a total of six trials.[2] For example, a possible trial sequence was one-object Switch, one-object No Switch, two-object Switch, two-object No Switch, three-object Switch, and three-object No Switch. All of the trials were coded later by two observers who were blind to whether they were coding No Switch or Switch trials and to the number of objects that had been hidden. Interobserver agreement on infants' search times averaged 94%.

Results

We examined infants' individuation performance by conducting a 3 (Memory Load: one, two, or three objects hidden) $\times$ 2 (Outcome: No Switch or Switch) $\times$ 2 (Load Order: ascending or descending memory load) $\times$ 2 (Switch Order: No Switch or Switch trial first) analysis of variance (ANOVA) on search time. This revealed a main effect of outcome, $F(1,15) = 17.85$, $p < .01$, $\eta_p^2 = .97$. Across all trials, infants searched longer on Switch trials ($M = 2.82$ s) than on No Switch trials ($M = 1.27$ s).

This main effect was moderated by a Memory Load $\times$ Outcome interaction, $F(1,15) = 5.24$, $p < .05$, $\eta_p^2 = .78$, suggesting that infants' success at individuating depended on the number of objects being remembered (Fig. 1). We investigated this interaction with a series of planned comparisons of infants' searching on Switch versus No Switch trials for each memory load. When one object had been hidden, infants searched longer on Switch trials ($M = 3.25$ s) than on No Switch trials ($M = 0.63$ s), $t(15) = 3.24$, $p < .01$, $d = 1.67$. When two objects had been hidden, infants also searched longer on Switch trials ($M = 3.42$ s) than on No Switch trials ($M = 1.03$ s), $t(15) = 4.78$, $p < .01$, $d = 2.47$. However, when three objects had been hidden, infants showed no difference in searching on Switch trials (1.78 s) versus No Switch trials (2.16 s), $t(15) = 0.50$, $p = .63$, $d = 0.26$. There were no other reliable main effects or interactions.

Discussion

The results of Experiment 1 suggest that 18-month-olds' ability to individuate depended on memory load. Infants appeared to have stored enough featural information to individuate when remembering one and two hidden objects. But when remembering three objects, infants failed. This result is striking given that across all Switch trials infants saw the identical change (e.g., a cat changed into a car) regardless of how many objects had been hidden. Infants' failure to individuate using this change when remembering three objects (in the face of their successful individuation using the same

[2] Infants actually were tested with two blocks containing six trials each, but the length of the experiment caused infants' searching to decline considerably during the second block; therefore, we excluded the second block from analysis.

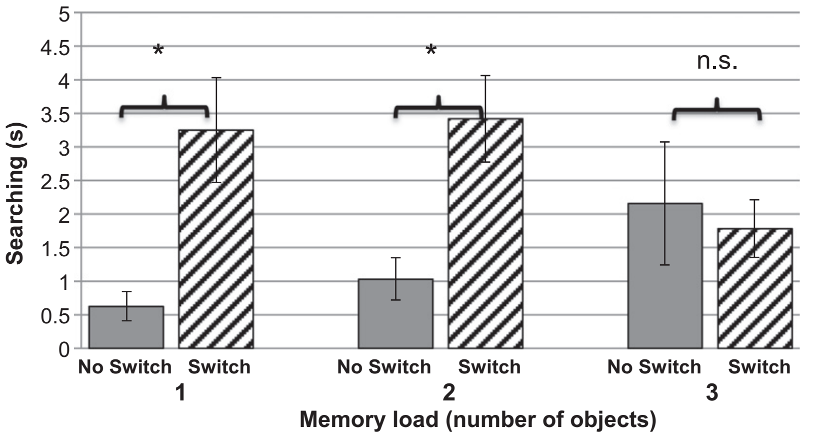

Fig. 1. Average search times on Switch and No Switch trials in Experiment 1 as a function of memory load. Bars depict standard errors. Asterisks denote $p < .05$.

change when remembering one or two objects) is unlikely to be due to a failure to encode or remember three numerically distinct objects. Several studies have shown that with durations similar to those used here, even younger infants correctly remember the *number* of hidden objects, continuing to search the box whenever three objects were hidden and fewer than three were retrieved (Feigenson & Carey, 2003, 2005). That infants remembered the presence of three objects (Feigenson & Carey, 2003, 2005), yet failed to use the objects' features to individuate, suggests that infants may remember three-object arrays with less featural precision than they remember one- and two-object arrays.

This interpretation predicts that the amount of featural difference between the hidden and retrieved objects should affect infants' success. Larger featural changes might support individuation even with infants' memory load filled to capacity. When remembering three objects, infants in Experiment 1 failed to detect large changes across superordinate kinds despite the fact that the hidden object differed from the retrieved object on the basis of color, shape, texture, and category membership, each of which has been shown to support object individuation when just a single object was being remembered (Bonatti et al., 2002; Wilcox, 1999; Xu et al., 2004). However, despite the many differences between the hidden and retrieved objects in this experiment, there were also some similarities. First, all of the objects (cat, shoe, bus, and car) were chosen to be roughly equally familiar to 18-month-olds. Second, the objects were roughly equally nameable by 18-month-olds (Fenson et al., 1994). Third, the objects were roughly equally complex in their number of parts and featural detail. Finally, the objects all behaved similarly with respect to basic principles of objecthood (Spelke, 1994). For example, all of the objects were solid cohesive entities—properties to which infants have demonstrated early sensitivity (Spelke et al., 1992; Spelke & Van de Walle, 1993).

In Experiment 2, we tested the hypothesis that remembering more objects results in a loss of featural resolution by asking whether infants would successfully individuate objects in three-object arrays when the contrast between the hidden and retrieved items was heightened. This time, on Switch trials we always switched one of the hidden objects with a nonsolid substance. The object-to-substance switch in Experiment 2 was predicted to be more salient than the object-to-object switch in Experiment 1 because the substance was expected to be less familiar to infants than the Switch objects used in Experiment 1, because the substance was unlikely to have a known label, because the substance was less featurally complex than the objects we used, and because previous research has shown that infants (Cheries, Mitroff, Wynn, & Scholl, 2008; Chiang & Wynn, 2000; Rosenberg & Carey, 2012) and adults (vanMarle & Scholl, 2003) often treat nonsolid substances differently than objects due to the failure of substances to maintain rigid boundaries. If infants presented with three-object arrays successfully use the switch between an object and a nonsolid substance to individuate, this would suggest that infants are able to store *some* featural information about items in three-object arrays (i.e., enough to detect a change from an object to a substance) but that this information is relatively sparse (i.e., too sparse to support detection of a change from an object to another object as in Experiment 1).

Experiment 2

The procedure was identical to that of Experiment 1 except that on Switch trials one of the hidden objects changed into a nonsolid substance made of gelatinous orange plastic. The substance lacked stable boundaries or a rigid shape and was easily deformable by grasping.

Method

Participants

The participants were 16 infants (7 girls and 9 boys, mean age = 18 months 23 days, range = 18 - months 6 days to 19 months 12 days). An additional 3 infants were excluded for fussiness (2) or for refusal to reach into the box (1).

Procedure

As in Experiment 1, on Switch trials the experimenter ensured that infants always retrieved the switched item (the nonsolid substance) themselves. The experimenter retrieved any remaining objects and handed them to the infants to examine briefly before all of the retrieved items were removed and the measurement period began. All aspects of the object presentation, measurement periods, and coding were identical to those of Experiment 1. Interobserver agreement averaged 93% across all trials.

Results

We examined infants' individuation performance by conducting a 3 (Memory Load: one, two, or three objects) × 2 (Outcome: No Switch or Switch) × 2 (Load Order: ascending or descending memory load) × 2 (Switch Order: No Switch or Switch trial first) ANOVA on search time. This revealed a main effect of outcome, $F(1,15) = 10.29$, $p < .01$, $\eta_p^2 = .84$. Overall, infants searched longer on Switch trials ($M = 2.52$ s) than on No Switch trials ($M = 1.06$ s). There was also a significant Memory Load × Load Order interaction, reflecting that regardless of outcome, infants searched longer on two- and three-object trials when those trials were presented in descending order rather than ascending order, $F(1,15) = 4.32$, $p < .05$, $\eta_p^2 = .69$.

Critically, unlike in Experiment 1, the main effect of outcome was not moderated by a Memory Load × Outcome interaction, $F(1,15) = 0.77$, $p = .48$, $\eta_p^2 = .17$. Regardless of whether one, two, or three objects had been hidden, infants searched longer after one of the objects switched into a nonsolid substance than when all of the objects maintained their original identity (Fig. 2). As in Experiment 1, we conducted a series of planned comparisons to examine infants' searching on Switch versus No Switch trials at each memory load. When one object had been hidden, infants searched longer on Switch trials ($M = 2.14$ s) than on No Switch trials ($M = 1.24$ s), $t(15) = 2.13$, $p = .05$, $d = 1.10$. When two objects had been hidden, infants also searched longer on Switch trials ($M = 2.69$ s) than on No Switch trials ($M = 0.83$ s), $t(15) = 2.31$, $p < .05$, $d = 1.19$. And when three objects had been hidden, infants still searched longer on Switch trials ($M = 2.75$ s) than on No Switch trials ($M = 1.13$ s), $t(15) = 2.19$, $p < .05$, $d = 1.13$.

To confirm that infants' ability to detect a change from an object into a nonsolid substance differed from their ability to detect a change from one object to a different object, we compared infants' performance in Experiments 1 and 2 (which were matched in every way except for the identity of the switched object). A 3 (Memory Load: one, two, or three objects) × 2 (Outcome: No Switch or Switch) × 2 (Experiment: 1 or 2) ANOVA on search time revealed a main effect of outcome, $F(1,31) = 22.90$, $p < .01$, $\eta_p^2 = .996$, with infants searching longer overall on Switch trials than on No Switch trials. This effect was moderated by a Memory Load × Outcome × Experiment interaction

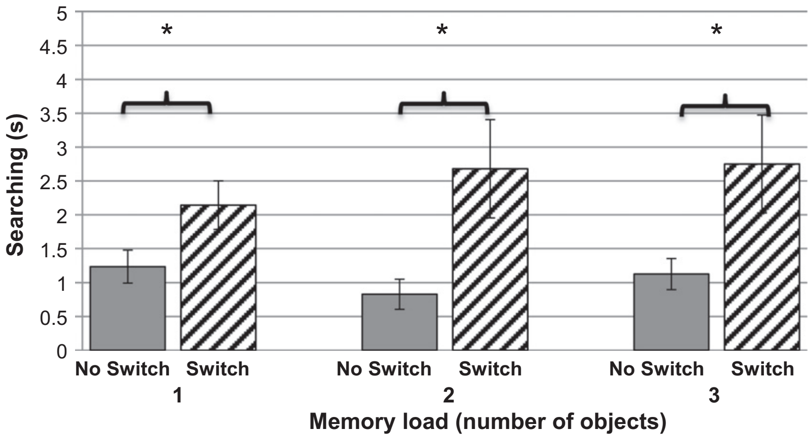

Fig. 2. Average search times on Switch and No Switch trials in Experiment 2 as a function of memory load. Bars depict standard errors. Asterisks denote $p < .05$.

$F(1,31) = 4.33$, $p < .05$, $\eta_p^2 = .73$), reflecting that infants successfully individuated three-object arrays in Experiment 2 but not in Experiment 1.

Infants' success across all memory loads in Experiment 2 suggests that, regardless of the number of objects being maintained in memory, infants noticed when any of these objects changed into a nonsolid substance. However, another possible explanation of our results is that infants continued searching the box on Switch trials across all memory loads simply because retrieving a nonsolid substance was stimulating enough to always prompt further searching.[3] To address this possibility, we tested a separate group of 9 infants, measuring whether infants increased their searching after retrieving a nonsolid substance, even after the expected number of objects had already been retrieved. Infants saw the same one, two, and three objects hidden as in Experiments 1 and 2. Half of the trials were identical to the No Switch trials of Experiments 1 and 2; infants saw exactly the same objects retrieved as they had just seen hidden. On the other half of the trials, first infants retrieved the same nonsolid substance as in Experiment 2, and then the experimenter retrieved all of the objects infants had originally seen hidden. For example, after seeing a cat, a shoe, and a bus hidden, infants retrieved a nonsolid substance and then the experimenter retrieved the cat, the shoe, and the bus. Infants were tested on both of these trial types at each memory load, and their order was counterbalanced across infants. If retrieving a nonsolid substance itself promotes further searching, then infants should show increased searching on these nonsolid substance trials. However, when averaging across memory loads, infants' searching on these "retrieve substance" trials (one-object $M = 1.73$ s, two-object $M = 0.83$ s, and three-object $M = 2.23$ s) did not statistically differ from their searching on trials where they retrieved only the originally hidden objects (one-object $M = 1.56$ s, two-object $M = 1.83$ s, and three-object $M = 1.83$ s), $t(8) = 0.33$, $p = .75$. Hence, it did not appear that having just retrieved a nonsolid substance caused infants to search.

Discussion

Infants in Experiments 1 and 2 were confronted with identical hiding arrays that differed only in whether an object subsequently switched into another object (Experiment 1) or into a nonsolid substance (Experiment 2). Yet, only infants in Experiment 2 detected the switch in identity. Because infants could not have known at the time of hiding what, if anything, one of the hidden objects would switch into, the memory representations that infants formed upon seeing the various arrays likely were similar across the two experiments. Apparently, it was the identity of the retrieved item that

[3] We thank Ed Awh for this suggestion.

determined whether infants successfully individuated. These results support the conclusion that when infants stored three objects in memory, they did so at a relatively coarse degree of resolution. This coarse resolution supported detection of a change from an object to a nonsolid substance, but not from one superordinate object kind to another.

The above argument—that the resolution of infants' object representations declines as memory load increases—hinges on the difference between Experiment 1 (in which one of three hidden objects changed into another object) and Experiment 2 (in which one of three hidden objects changed into a nonsolid substance). Because our interpretation of infants' abilities relies on a failure (in the three-object trials of Experiment 1), we wished to replicate this failure in order to draw firmer conclusions. To this end, we conducted a final experiment in which we presented infants with the same one-, two-, and three-object arrays as in Experiments 1 and 2. To provide an even stronger test of our prediction that infants would fail to individuate when remembering three objects, on Switch trials in Experiment 3 *all* of the hidden objects changed identity across superordinate kind regardless of memory load. For example, infants saw a cat, a shoe, and a bus hidden, and then they saw a car, a duck, and a brush retrieved. If infants' object representations when remembering three-object arrays are less featurally precise than when remembering just a single object, they should show poorer individuation performance with three-object arrays than with one-object arrays despite the fact that on Switch trials the three-object arrays offer three times as many opportunities to detect a switch in object identity than the one-object arrays.

Experiment 3

The procedure was identical to that of Experiment 1 except that on Switch trials all of the hidden objects changed into other objects.

Method

Participants

The participants were 16 infants (8 girls and 8 boys, mean age = 18 months 24 days, range = 18 months 3 days to 19 months 14 days). An additional 2 infants were excluded for searching more than 3 standard deviations from the group mean across multiple trials (1) or for refusal to reach into the box (1).

Procedure

As in Experiments 1 and 2, infants saw a cat, a shoe, and a bus hidden. On No Switch trials, infants retrieved these same objects; on Switch trials, they retrieved one or more objects from a set that included a red metal car, a yellow plastic duck, and a blue plastic brush with white bristles (Table 1). All aspects of the object presentation, measurement periods, and coding were identical to those of Experiments 1 and 2 except that on Switch trials all of the objects that had been hidden switched identity (these objects all were pre-loaded into the box prior to each Switch trial). Which object infants retrieved (and which object the experimenter retrieved for them) was counterbalanced across infants. Interobserver agreement averaged 93% across all trials.

Results

We examined infants' individuation performance by conducting a 3 (Memory Load: one, two, or three objects) × 2 (Outcome: No Switch or Switch) × 2 (Load Order: ascending or descending memory load) × 2 (Switch Order: No Switch or Switch trial first) ANOVA on search time. This revealed main effects of outcome, $F(1,15) = 5.52$, $p < .05$, $\eta_p^2 = .58$, and memory load, $F(1,15) = 4.21$, $p < .05$, $\eta_p^2 = .68$. The main effect of outcome was driven by the fact that, collapsed across the three memory loads, infants searched longer on Switch trials ($M = 2.51$ s) than on No Switch trials ($M = 1.29$ s). The main effect of memory load was driven by the fact that infants searched longer on two-object trials ($M = 2.56$ s) than on one-object trials ($M = 1.33$ s) and three-object trials ($M = 1.80$ s), collapsed across Switch and No Switch trials.

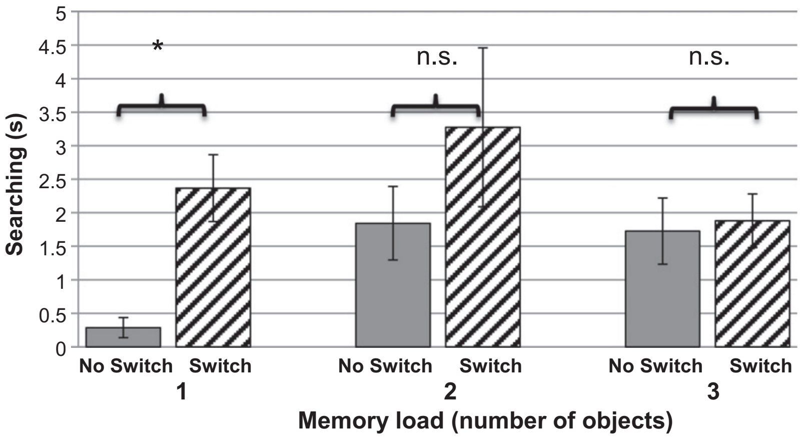

Fig. 3. Average search times on Switch and No Switch trials in Experiment 3 as a function of memory load. Bars depict standard errors. Asterisks denote $p < .05$.

Although we did not observe a Memory Load × Outcome interaction, $F(1,15) = 1.17$, $p = .33$, $\eta_p^2 = .23$, we conducted planned comparisons of Switch and No Switch trials at each memory load as we did in Experiments 1 and 2. We found that when one object was hidden, infants searched longer on Switch trials ($M = 2.37$ s) than on No Switch trials ($M = 0.29$ s), $t(15) = 3.62$, $p < .01$, $d = 1.87$, but that when three objects had been hidden, infants searched equally on Switch and No Switch trials (Switch trials $M = 1.88$ s and No Switch $M = 1.73$ s), $t(15) = 0.23$, $p = .82$, $d = 0.12$. When two objects had been hidden, infants searched longer on Switch trials ($M = 3.28$ s) than on No Switch trials ($M = 1.84$ s), but this difference was not statistically significant, $t(15) = 1.12$, $p = .28$, $d = 0.57$ (Fig. 3).

We also observed a Memory Load × Switch Order interaction, $F(1,15) = 3.87$, $p < .05$, $\eta_p^2 = .64$. Although not relevant to our central hypothesis, this interaction reflected that infants who saw No Switch trials presented first searched longer overall when three objects had been hidden than when one or two objects had been hidden, collapsed across No Switch and Switch trials. There were no other reliable main effects or interactions.

Infants in Experiment 1 successfully searched longer on Switch trials with a memory load of one or two objects but not with a memory load of three objects. Infants in Experiment 3 searched longer on Switch trials with a memory load of one object but not with a memory load of two or three objects. The only difference between these experiments was whether just a single object changed identity on Switch trials (Experiment 1) or whether all objects changed identity (Experiment 3). To ask whether infants performed differently depending on the number of objects that changed identity on the Switch trials, we conducted a 3 (Memory Load: one, two, or three objects) × 2 (Outcome: No Switch or Switch) × 2 (Experiment: 1 or 3) ANOVA on search time. This revealed a main effect of outcome, $F(1,31) = 21.58$, $p < .01$, $\eta_p^2 = .99$, with infants in both experiments searching longer overall on Switch trials than on No Switch trials. This was moderated by a Memory Load × Outcome interaction, $F(1,31) = 4.87$, $p < .05$, $\eta_p^2 = .78$, reflecting that across both experiments infants' success depended on the number of objects hidden. Importantly, we did not observe a Memory Load × Outcome × Experiment interaction, $F(1,31) = 0.42$, $p = .66$, $\eta_p^2 = .12$. Despite the finding that infants in Experiment 3 did not search significantly longer on Switch trials than on No Switch trials with a memory load of two objects, their performance was statistically indistinguishable from that of infants in Experiment 1. Infants performed no better when all of the objects in the hiding array switched identity than when only one object switched identity.

Discussion

The results of Experiment 3 confirm and extend our earlier finding that infants' individuation abilities depend on the number of objects being remembered. When remembering one and perhaps two hidden objects, infants appear to have stored enough featural information to detect object switches and use these to individuate (although this was not statistically significant on two-object trials). But when remembering three objects, infants failed to individuate. This result is striking given the large amount of change between the hidden array and the retrieved array. If infants had remembered the identity of even one of the three hidden objects, they should have continued seeking the missing object and, thereby, should have searched longer on Switch trials than on No Switch trials. This is true regardless of which particular feature(s) infants stored in memory; because on Switch trials the retrieved objects differed from the hidden objects in color, texture, shape, and category membership, infants could have used any of these features, from any one of the objects in the array, to successfully individuate. That they did not do so suggests that infants might not have represented the features of three-object arrays as precisely as those of one-object arrays.

General discussion

In three experiments, we investigated the ways in which memory constrains early individuation abilities. First, we asked whether 18-month-old infants can individuate when remembering more than just a single object. Previous studies tested infants' individuation abilities when just one object was being maintained in memory and was compared with a single visible object (e.g., Wilcox, 1999; Xu & Carey, 1996). In the current series of experiments, we found that 18-month-olds also successfully individuated when two objects (Experiments 1 and 2) and three objects (Experiment 2) were being maintained in memory and were compared with an array of visible objects. Hence, even when faced with arrays of multiple moving objects coming in and out of occlusion, infants track object identities and use this information to solve the problem of individuation.

Second, we asked whether memory load affected infants' individuation abilities. We found that it did; in both Experiments 1 and 3, infants successfully individuated when maintaining just a single object in memory but failed to use the exact same change in object features to individuate when maintaining three objects in memory. Several previous studies found that in a task very similar to that used here, even younger infants remembered how many objects were hidden when shown arrays of one, two, and three objects (Feigenson & Carey, 2003, 2005). This suggests that in our experiments infants likely represented the number of objects in the array, but with larger arrays they were unable to remember or use the objects' features in order to solve the individuation problem.

Our results are consistent with the interpretation that infants' object representations lost featural precision as the number of remembered objects increased. Evidence for this comes from a comparison between Experiments 1 and 2. Infants failed to individuate when one of three objects switched into a different object across superordinate kinds (Experiment 1), but they succeeded when one of three objects switched into a nonsolid substance (Experiment 2). The nonsolid substance was chosen to contrast with the target object in its familiarity, likelihood of having a known label, internal complexity, and ontological kind (it remains open whether all of these contrasts played a role in supporting infants' successful individuation or whether one or more of these was more central). This finding that the object–substance contrast supported individuation, whereas the object–object contrast did not, suggests that infants might not have remembered the objects in a three-object array in enough detail to allow the detection of a mismatch between what was hidden and what was retrieved. Indeed, previous research has also found that infants sometimes demonstrate accurate representations of the number of objects in a scene yet fail to accurately represent the features of the object(s) (Kibbe & Leslie, 2011; Wilcox & Schweinle, 2002). Our current results suggest that the degree to which object features are remembered, or are used to empower individuation, may depend on memory load.

One alternative interpretation to this claim is that when remembering three-object arrays in Experiments 1 and 3, infants might have failed to individuate not because of a loss of featural precision but rather because of the upper bound on working memory. Across many studies, infants have been shown to store a maximum of approximately three object representations concurrently in working memory (Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002; Ross-Sheehy et al., 2003). Consider, for example, the three-object Switch trials in Experiment 1. Infants saw three objects hidden and then saw two of these objects plus one additional object retrieved. Might infants have failed to individuate because, at this point, four distinct objects had been seen, thereby overloading memory? Although the task did not require infants to store representations of the three *retrieved* objects in memory, seeing them might have "overwritten" some or all of infants' representations of the three originally hidden objects. However, infants' success on the three-object Switch trials of Experiment 2 provides evidence against this interpretation. On the three-object Switch trials of Experiment 2, infants also saw three distinct objects hidden and then saw two of these objects plus a novel item (a nonsolid substance) retrieved—again a total of four featurally distinct items. In this case, infants apparently remembered the number of hidden objects but required a very large contrast between what was hidden and what was retrieved in order to continue searching for the missing object.

These results are relevant to a debate that has emerged from the literature on adult working memory. On one side of this debate are models that view adult working memory capacity as fixed. These models posit a limit on the number of items that working memory can store regardless of the items' features (Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997; Scolari, Vogel, & Awh, 2008; Zhang & Luck, 2008). An implication of this view is that remembering more items does not decrease the featural resolution of the items' representations. In contrast, variable-capacity models view memory representations as competing for a shared resource pool. As more representations are stored, less of this resource may be available for representing the features of the memoranda, resulting in a trade-off between capacity and resolution (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; Wilken & Ma, 2004; Xu & Chun, 2006).

Although our findings more closely align with variable-capacity models than with fixed-capacity models of working memory, they are also compatible with two hybrid models of working memory. First, they are compatible with the view that a fixed number of items can be stored in working memory but that an item can be redundantly represented if extra memory slots are available, thereby increasing representational resolution (Zhang & Luck, 2008). According to this account, an observer can represent an item in one slot and also represent the same item in additional slots. The observer then averages these redundant representations, resulting in an increase in representational precision. Our findings also are compatible with the view that representing objects in working memory involves two stages: one in which coarse representations are only little affected by the number of items being maintained and another in which representations with finer resolution are affected by memory load (Gao et al., 2009). It is possible that when hidden and retrieved items were very different from each other (as with the object vs. nonsolid substance contrast in Experiment 2), infants' ability to detect change was little affected by the number of items being remembered. But when a finer degree of resolution was necessary (as in Experiments 1 and 3), change detection may have been affected by the number of items occupying working memory.

Our results also raise the question of how memory load and featural precision interact at various stages of memory processing. One possibility is that our results reflect an interaction between array size and the initial process of encoding items into working memory. There are at least two ways in which array size and encoding might interact. First, infants might be less likely to encode and form a representation of any particular individual object as the number of presented objects increases. Never having stored representations of the hidden objects would, of course, lead to failure to individuate because there would be no representations being held in working memory to compare with the retrieved objects. However, the results of Experiment 2 argue against this. The object arrays used in Experiments 1 to 3 were identical, with the only difference being what was retrieved *after* the objects had been hidden. Yet, only in Experiment 2 did infants detect a change when one of these objects switched identity. Because infants could not have known at the time of array presentation whether one of the objects in the array was going to switch into a different object (Experiment 1) or into a nonsolid substance (Experiment 2) or whether *all* of the objects in the array were going to switch into different objects (Experiment 3), infants must have encoded and stored representations of all three objects in order to have succeeded in Experiment 2.

A different version of an encoding account is that when more objects were present, infants encoded each object but with less featural precision. For example, infants might have encoded more features of the object in a one-object array (e.g., that the hidden item was a fuzzy white cat in an upright posture) than they encoded when faced with that very same object in the presence of additional objects (e.g., that the hidden item was an animal or was an object). The coarse featural representation of an object in a three-object array may have been sufficient to allow infants to distinguish between the hidden object and a nonsolid substance (as in Experiment 2) but insufficient to allow infants to distinguish between the hidden object and a different object (as in Experiments 1 and 3).

Alternatively, infants may have encoded the objects with equal featural precision across the different array sizes, but with larger arrays may have been less successful at maintaining the features once the items entered working memory. For example, interference accounts suggest that working memory representations can mutually disrupt one another, with remembered features sometimes being distorted or overwritten (Oberauer & Kliegl, 2006). Finally, infants may have both encoded and maintained object representations with equal featural precision across the different array sizes, but may have had more difficulty in retrieving or using those featural representations when more objects were present. For a related discussion of whether the phenomenon of change blindness in adults is caused by a failure during encoding, maintenance, or retrieval, see Simons and Rensink (2005).

In summary, the current results show that infants can individuate when maintaining multiple object representations in memory but that individuation suffers with increasing memory load. Infants required larger identity changes to individuate when remembering three objects than when remembering one or two objects. This suggests that the resolution of infants' memory representations might not be fixed but rather may change depending on the number of items being stored.

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