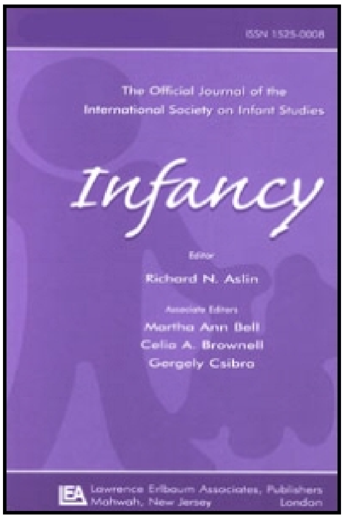

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Limits on Infants' Ability to Dynamically Update Object Representations

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Limits on Infants' Ability to Dynamically Update Object Representations

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Like adults, infants use working memory to represent occluded objects and can update these memory representations to reflect changes to a scene that unfold over time. Here we tested the limits of infants' ability to update object representations in working memory. Eleven-month-old infants participated in a modified foraging task in which they saw 2 quantities of crackers sequentially hidden in buckets and then were allowed to choose between them. We manipulated the working memory demands of the task by either hiding crackers in direct succession (i.e., infants saw all of the crackers hidden in the first location, then saw all of the crackers hidden in the second location), or hiding them in alternation (i.e., infants saw some crackers hidden in the first location, then saw some crackers hidden in the second location, then saw more crackers hidden in the first location). Across 6 experiments we found that infants successfully updated their representations of the hidden arrays when crackers were presented in succession. However, when crackers were hidden in alternation and infants had to reupdate an array that was no longer in the current focus of attention, infants showed a striking pattern of failure. These results suggest that, for infants as well as for adults, the flexibility of working memory is subject to processing constraints.

The ability to represent objects is fundamental to everyday interaction with the environment. Yet, object representation is fraught with challenges. Objects must be conceived of as persisting individuals despite shifts in perceptual conditions such as luminance and viewing angle. Worse, objects often must be represented in the absence of raw sensory data, as when they have undergone occlusion by an intervening surface. Finally, object representations must be dynamically updated to ac-

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count for changes that unfold over time, as when objects are added to or removed from a scene. Previous work has shown that many of these object representation problems are solved early in life—young infants represent and track persisting objects in the face of changing viewing conditions (e.g., Granrud, 2006) and occlusion (for review, see Baillargeon, 1999, 2002). However, much less is known about how young observers solve the problem of updating object representations over time to account for changes to a scene. Here we show that infants face a surprising limitation to this ability. Our results suggest that, once formed, infants' object representations are remarkably resistant to subsequent change.

INFANTS REPRESENT OCCLUDED OBJECTS

Young infants can represent objects even when the objects are hidden by temporary darkness (Shinskey & Munakata, 2003) or occlusion (for review see Baillargeon, 1999, 2002). For example, 2.5-month-old infants increase their looking when an object hidden behind one occluding screen is retrieved from behind a different screen (Wilcox, Nadel, & Rosser, 1996). Four-month-old infants expect that a box hidden by a rotating screen continues to exist and will block the path of the moving screen (Baillargeon, 1987). Furthermore, infants use their representations of hidden objects to make inferences about how multiple occluded objects should interact. After being habituated to a toy car rolling down a ramp, infants saw a box placed either on top of or behind the ramp and then the apparatus was covered by a screen. Six- and 8-month-old infants correctly inferred that a box would stop the car if it had been placed on the ramp (Baillargeon, 1986), suggesting that they understood how the two objects should interact even though they were not able to see them.

INFANTS UPDATE OBJECT REPRESENTATIONS

Beyond merely representing hidden objects, infants can also mentally update representations of hidden object arrays in response to new events. For example, 5-month-old infants who see an object become hidden by an occluding screen, then see a second object placed behind the same screen, correctly expect that two objects will be revealed when the screen is lifted (Koechlin, Dehaene, & Mehler, 1997; T. Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992).[1]

[1] Although infants in some versions of this task have been shown to base their expectations on the total continuous extent (e.g., total area) of the array rather than on the number of individuals in the array (Feigenson, Carey, & Spelke, 2002), infants can also form expectations based on discrete number (Cheries, Decoste, & Wynn, 2003). Whether infants are representing the total number of objects or the total continuous extent behind the screen, these studies show that infants are updating memory representations of hidden arrays. For further discussion of infants' ability to represent both discrete and continuous properties of object arrays, see Feigenson (2005) and Feigenson, Dehaene, and Spelke (2004).

To succeed at this, infants must represent the initial array (comprised of Object A), maintain that representation once the array is hidden, then update the representation to include Object B. In this way, a representation of a single occluded object is updated to that of two occluded objects. Infants can also update in the reverse direction to reflect an object's departure from an array. Infants who see a two-object array hidden behind a screen, then see an object removed from behind the screen, correctly expect that just one object will be revealed when the screen is lifted (T. Simon et al., 1995; Wynn, 1992).

To know how many objects were behind the screen, infants had to serially update their representation of the hidden array each time an object was added or removed. Here, we use the term *updating* to refer to the operation of altering a representation of a hidden object or array to reflect changes made outside of immediate perceptual experience. In the experiments by Wynn and colleagues, infants never actually saw an array containing two objects until the test outcomes were revealed—instead they had to infer the presence of two objects by updating the initial representation of the hidden array when the experimenter added an object. Wynn's (1992) experiments show that infants can perform this kind of updating of hidden arrays by 5 months of age.

INFANTS UPDATE ACROSS MULTIPLE SPATIAL LOCATIONS

Experiments like those previously described, using toy objects on a puppet stage, can be thought of as highly simplified versions of the real-world scenes that confront infants daily. Outside of the laboratory, infants are faced with more complex environments containing many varied objects and many opportunities for objects to occlude one another. This raises the question of whether infants can maintain and update object representations under these more complex circumstances, when larger numbers of objects and hiding locations are involved.

One line of research has found that infants can indeed update representations of object arrays that are hidden in at least two distinct spatial locations. Feigenson, Carey, and Hauser (2002) presented 10- and 12-month-old infants with a choice between two quantities of crackers hidden in buckets at a distance of several feet from one another. Infants observed, for example, one cracker hidden in one bucket, followed by two crackers hidden serially in the other (a one vs. two choice, with order and side of presentation counterbalanced). Following the presentation, infants' significant preference to approach the bucket with the greater quantity indicated that they had successfully updated representations of hidden object arrays with presentations of one versus two and two versus three crackers, and performed an ordinal comparison on the resulting memory representations. However, infants chose at chance with comparisons of three versus four, two versus four, three versus six, and even one versus four crackers (Feigenson & Carey, 2005; Feigenson et al., 2002). The finding that performance was not determined by the ratio between quantities but by the absolute number of crackers presented suggests that infants were constrained by the number of objects they could simultaneously represent, or by the number of times an object array had to be mentally updated, with an upper limit of three per hiding location. Infants' success when presented with two versus three crackers shows that, by 10 months, infants can serially update a representation of a hidden array up to three times across each of two locations. Hence, infants' working memory is flexible enough to allow for representation of complex scenes involving multiple objects (that are never simultaneously viewed) across multiple locations. This ability goes beyond the mere formation of static object representations, as it allows infants to form representations of object arrays that reflect subsequent changes unfolding over time.

CAN INFANTS REUPDATE OBJECT REPRESENTATIONS?

The preceding experiments, as well as other experiments involving smaller numbers of occluded objects (Huntley-Fenner, Carey, & Solimando, 2002; Kaldy & Leslie, 2003; Uller, 1999), demonstrate that infants can update object representations at multiple hiding locations. However, in all of these experiments updating was always constrained to start and finish at a given hiding location before beginning at a second location. For example, in the cracker choice experiments, infants always saw the entire contents of a bucket serially placed in that bucket before any crackers were presented elsewhere—the experimenter never alternated cracker placements between the two buckets. However, real-world events rarely unfold in so orderly a fashion. Attention often must shift back and forth between locations, as when a parent puts some pieces of fruit in a bowl, then fills a cup with juice, then puts another piece of fruit in the bowl. This type of reupdating requires not only that infants dynamically update a representation over time, but also that the resulting representation remain flexible enough to be altered (added to or subtracted from) even after infants have shifted their attention to track objects in a different part of the scene. To our knowledge, no experiments to date have examined this ability in infants, asking whether infants can dynamically reupdate object representations as they watch unfolding changes to a scene. However, a related ability has been explored in the literature on adults' working memory, and appears to pose some special challenges (Garavan, 1998; Jiang & Kumar, 2004; Jiang, Kumar, & Vickery, 2005; Oberauer, 2003). In the "General Discussion" section we discuss this adult reupdating literature with respect to infants' performance in our reupdating task.

We examined infants' reupdating using the cracker choice paradigm, which has the advantages of being simple, naturalistic, and yielding a clear behavioral measure. Each infant received a single trial in which he or she chose between two quantities of hidden crackers. We only presented infants with quantities already known to be within their working memory capacity (Feigenson & Carey, 2003, 2005; Feigenson et al., 2002). In Experiment 1 we replicated infants' success at representing and comparing one versus two objects when objects were presented in direct succession (e.g., two crackers sequentially placed in location A, then one cracker placed in location B). Next, in Experiment 2 we asked whether infants can reupdate representations of object arrays after forming representations of other objects elsewhere in the scene. We did this by alternating object presentation between the two hiding locations (e.g., one cracker placed in location A, one cracker placed in location B, a second cracker placed in location A). A control condition asked whether any effects of reupdating were caused by mere attentional switches or amount of movement in the event presentation, as opposed to the demands of altering a stored memory representation. To preview our results, we found that reupdating posed a particular challenge for infants. Finally, in Experiment 3 we investigated the fate of the representation that infants had unsuccessfully tried to reupdate, asking whether the process of reupdating was ignored and the initial array was preserved, or whether reupdating overwrote the initial object representation.

EXPERIMENT 1

In several previous experiments, 10- to 12-month-old infants successfully remembered and compared quantities when one object was hidden in one location and two objects were hidden in another location (Cheries, Mitroff, Wynn, & Scholl, 2008; Feigenson et al., 2002; vanMarle & Wynn, submitted). In all of these, the two-object array was always presented serially in direct succession such that infants never had to reupdate a representation after moving their attention elsewhere in the scene. Before asking whether infants can reupdate representations of hidden arrays, we first sought to replicate this finding that infants can perform the simple version of updating required by a one versus two-object comparison, with objects presented in direct succession. We also probed for any effects of serial order on infants' memory of the arrays by presenting one group of infants with a choice in which one object was presented first (Condition ABB), and a separate group of infants with a choice in which two objects were presented first (Condition AAB).

Method

Participants. Seventeen healthy full-term infants between 10 and 13 months old participated in Condition ABB (*M* age = 11 months; 16 days, range =

11;0–12;0) and 15 participated in Condition AAB (*M* age = 11 months; 10 days, range = 9;16–12;20). Approximately half of the infants in each condition were boys (10 in Condition ABB and 8 in Condition AAB). Fifteen additional infants were excluded due to fussiness, failure to choose between the buckets (see later), or parental interference.[2]

Stimuli. Infants watched an experimenter hide 6.5 cm × 3 cm graham crackers sequentially in two identical opaque plastic buckets. The buckets (13 cm diameter, 14.5 cm high) were too tall for infants to see inside.

Design and procedure. Infants sat on a parent's lap or in front of the parent on a playroom floor approximately 100 cm from the experimenter. The session began with a familiarization trial in which infants saw the experimenter hide a toy in a small container. The experimenter then encouraged infants to crawl or walk to the container to retrieve the toy. If infants did not immediately do so, the experimenter and parent provided verbal encouragement. After infants had successfully retrieved the toy, the critical trial was introduced.

For the single critical trial, parents were instructed to remain silent and to refrain from providing any cues. The experimenter introduced the two buckets simultaneously, showing infants that they were empty by turning the buckets upside down and shaking them. She placed the buckets on the floor approximately 70 cm to 100 cm from the infant and 35 cm to 40 cm from either side of the midline, so that infants could not reach both at once. For each cracker placement, the experimenter brought out one cracker and held it above one of the buckets. She showed it to infants, saying, "Look at this," then placed it in the bucket while ensuring that infants watched. In Condition ABB the experimenter placed one cracker in bucket A, then sequentially placed two crackers in bucket B. In Condition AAB the experimenter sequentially placed two crackers in bucket A, then placed one cracker in bucket B. Whether bucket A was to infants' left or right was counterbalanced within each condition (and therefore the A vs. B notation refers to the crackers' temporal presentation rather than their spatial presentation). After the presentation, the experimenter looked down at the midline to avoid providing any cues. Parents restrained infants until after the last cracker had been presented, at which point infants were allowed to approach either bucket. If infants did not approach within 10 sec, the experimenter gave verbal encouragement without looking up. If infants still did not approach within 10 more sec, the experiment was terminated. Infants were considered to have chosen when they either reached into one of the

[2]Attrition rates from previous experiments using a similar choice task ranged from 11% to 27% (Cheries et al., 2008; Feigenson & Carey, 2005; Feigenson et al., 2002). Although our attrition rate (47%) was higher than that in other experiments, infants in our task still replicated previous results, suggesting that they were generally representative of infants of this age.

buckets, or approached a bucket and sat in front of it for at least 8 sec. Choices were videotaped, and agreement between observers who later viewed the tapes was 100%.

Results and Discussion

The results are shown in Figure 1. In Condition ABB, when one cracker was presented first, 13 of 17 infants approached the bucket containing the greater number of crackers ($p < .05$, two-tailed sign test). In Condition AAB, when two crackers were presented first, 12 of 15 infants approached the bucket containing the greater number ($p < .05$, two-tailed sign test). There were no effects of sex or of side (whether one cracker was hidden in the left or right bucket).

These successes replicate those obtained in previous experiments (Cheries et al., 2008; Feigenson et al., 2002; vanMarle & Wynn, submitted), confirming that infants can (a) store a representation of a single hidden cracker in working memory, (b) update that representation when a second cracker is added, (c) maintain the resulting representation while attention is shifted to a different spatial location, (d) store a representation of a single cracker in that new location, and (e) make an ordi-

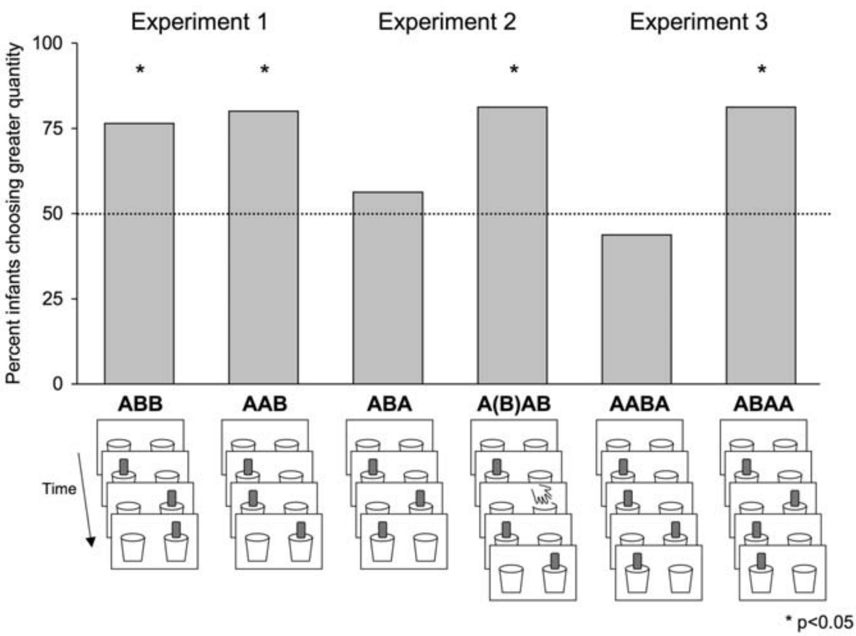

FIGURE 1 Percentage of infants choosing the greater quantity across the six conditions. Dotted line indicates chance performance.

nal comparison between the two remembered crackers in the first bucket and the one cracker in the second. Infants can also do this when the order of the cracker placement is reversed. With infants' updating abilities confirmed, we are now poised to ask whether infants can also reupdate representations of object arrays.

EXPERIMENT 2

Method

Participants. Sixteen healthy full-term infants between 9 and 13 months old participated in Condition ABA (*M* age = 11 months; 19 days, range = 10;2–13;2) and 16 participated in attentional control Condition A(B)AB (*M* age = 11 months; 9 days, range = 9;29–12;25). Approximately half of the infants in each condition were boys (6 in Condition ABA and 7 in Condition A(B)AB). Seven additional infants were excluded due to fussiness, failure to choose between the buckets, or parental interference.

Stimuli. The stimuli were identical to those used in Experiment 1.

Design and procedure. Condition ABA tested infants' ability to reupdate by presenting crackers in alternating order between the two buckets. Infants saw one cracker hidden in the first bucket, one cracker in the second, and then one more in the first (whether the presentation began on the right or the left side was counterbalanced). As in Conditions ABB and AAB, the experimenter always made sure infants were watching each cracker placement prior to hiding. Note that both the total number of crackers and the number of crackers in each bucket were identical to those in Experiment 1. However, working memory demands were greater in Condition ABA because infants had to reupdate a representation that had already been stored in memory and was no longer being held in the current focus of attention. Infants should choose the bucket with two crackers only if they can successfully reupdate a previously stored representation.

However, the alternating cracker presentation in Condition ABA also requires more shifts of attention, because infants had to return their attention back to the original hiding location in Condition ABA but not in Conditions ABB or AAB. That is, Condition ABA requires infants to make two attentional shifts before making their choice, whereas Conditions ABB and AAB required only one attentional shift. Condition A(B)AB was designed to control for this difference in low-level task demands. Like Condition ABA (and unlike Conditions ABB and AAB), Condition A(B)AB required infants to alternate their attention between two buckets. Like Conditions ABB and AAB, however (and unlike Condition ABA), all of the crackers to be hidden in the first bucket were presented before the introduction of any crackers that were to be hidden in the second bucket. This was accomplished by inserting an empty hand wave in between the two successive cracker placements in the first bucket (as shown in Figure 1). Infants first saw one cracker placed in the first bucket. The experimenter then waved her empty hand above the second bucket and said, "Look at this." Next, she placed a second cracker in the first bucket, followed by one cracker in the second bucket (the parenthetical B in the A(B)AB condition notation refers to the intervening hand wave). This resulted in two total crackers in the first bucket and one cracker in the second. Crucially, although this condition required infants to switch their attention to the second bucket before all of the crackers were placed in the first bucket, it did not require infants to reupdate a representation of a hidden object array. Infants never had to modify their representation of the contents of the first cracker array after the second array had been introduced.[3]

Results and Discussion

The results are shown in Figure 1. In Condition ABA, only 9 of 16 infants chose to approach the greater quantity (*ns*, $p = .804$, two-tailed sign test). Infants appeared unable to reupdate a stored representation once working memory had been deployed elsewhere in the scene, despite the fact that the total number of crackers presented was well within their working memory capacity (Feigenson et al., 2002) and despite the success of infants of this age in choosing two crackers over one across at least five previous experiments (Conditions ABB and AAB from Experiment 1; Cheries et al., 2008; Feigenson et al., 2002; vanMarle & Wynn, submitted). Infants appear limited in their ability to dynamically reupdate representations of hidden arrays.

In Condition A(B)AB, 13 of 16 infants successfully chose to approach the side with more crackers ($p < .05$, two-tailed sign test). There were no effects of sex or of side of presentation. Thus, when the shift of attention back to the first bucket did not require an update of its represented contents, infants successfully represented both arrays.

The results of Experiment 2 suggest that even though infants consistently represent the sequential hiding of one versus two objects (as shown by Conditions ABB and AAB of Experiment 1 and by previous studies), infants cannot represent one versus two objects when those objects are hidden in temporal alternation. Condition A(B)AB demonstrates that this failure is not due to shifting attention within a scene. Indeed, Condition A(B)AB required more shifts of attention than Condition ABA, yet infants still succeeded. We suggest that this is because infants can only

[3]Rate of cracker presentation was designed to be approximately equal across all conditions, but did vary somewhat. However, variation in rate or total duration of the presentation sequence did not systematically predict infants' pattern of success or failure across all of the conditions we tested (see Figure 2).

update object representations that are held in the current focus of attention. Once infants begin tracking objects elsewhere in a scene, a stored representation becomes rigidly fixed, and reupdating it is difficult or impossible.

This failure raises questions about the fate of the original representation that infants tried (but failed) to reupdate. Does the attempt to reupdate destroy the original representation? Alternatively, is the attempt to reupdate simply ineffective, leaving the original object representation preserved? Infants' lack of a systematic preference in Condition ABA does not decide between these two possibilities. Infants might have chosen at random because the attempt to reupdate destroyed the original representation of the one object in the first bucket. On this account, infants would have stored a representation of a cracker in the first bucket, then stored a representation of a cracker in the second bucket. When infants saw the final cracker being hidden in the first bucket and tried to reupdate their representation of the hidden array, the representation of the original cracker was overwritten or destroyed, leaving only the representation of the most recently presented cracker in the first bucket and the cracker in the second bucket: a one versus one choice. Alternatively, infants might have chosen at random because reupdating simply failed. On this account, infants would have stored a representation of a cracker in the first bucket, then stored a representation of a cracker in the second bucket. When infants saw the final cracker being hidden in the first bucket and tried to reupdate their representation of the hidden array, they were unable to do so. This left only the representation of the first cracker that was placed in the first bucket and the cracker in the second bucket, another one versus one choice. Because both of these accounts are consistent with the random choice we observed in Condition ABA, we next manipulated the number of objects presented both before and after infants' attempt to reupdate so that we could identify the locus of infants' reupdating failure.

EXPERIMENT 3

Method

Participants. Sixteen healthy full-term infants between 9 and 13 months old participated in Condition AABA (*M* age = 11 months; 3 days, range = 9;21–12;23), and 16 participated in Condition ABAA (*M* age = 11 months; 14 days, range = 9;25–12;18). Approximately half of the infants in each condition were boys (10 in Condition AABA and 9 in Condition ABAA). Eight additional infants were excluded due to fussiness, failure to choose between the buckets, or parental interference.

Stimuli. The stimuli were identical to those in Experiments 1 and 2.

Design and procedure. Condition AABA tested the hypothesis that attempting to reupdate a stored representation of an object array destroys or overwrites that representation. Infants saw two crackers placed in direct succession into the first bucket, then saw one cracker placed in the second bucket, and finally one more cracker in the first bucket (see Figure 1). If infants' attempt to reupdate the array destroys the original representation, then infants should represent this sequence as a choice between one cracker versus one cracker and should therefore chose randomly. Alternatively, if infants fail to reupdate but can still maintain the original representation of the hidden array, then infants should represent this sequence as a choice between two crackers versus one cracker and should therefore prefer to approach the first bucket.

Condition ABAA tested the converse hypothesis that instead of maintaining the original representation during the reupdate, infants overwrite the previous contents of the array and form a new object representation at the location of the original bucket. Infants saw one cracker placed in the first bucket, one cracker in the second bucket, and then two more crackers placed in direct succession into the first bucket (see Figure 1). If infants can form a new representation at the old location, they should represent this sequence as a choice between two crackers versus one cracker and should therefore prefer to approach the first bucket. If infants cannot form a new representation at the old location, they should represent this sequence as no crackers versus one cracker and should therefore prefer the second bucket.

Results and Discussion

The results are shown in Figure 1. In Condition AABA, infants demonstrated no systematic preference, with 7 of 16 choosing the bucket with the larger quantity (*ns,* $p = .804$, two-tailed sign test). There were no effects of sex or side of presentation. These results suggest that attempting to reupdate a stored object representation destroys or overwrites that representation. The robustness of this tendency to "rewrite" the initial memory representation remains an open question. Here, infants appeared to replace their initial representation of the two crackers initially placed in bucket A with a representation of the one cracker placed in bucket A after the intervening placement in bucket B. Whether infants would perform similarly when given a very large difference between the initial and the final arrays (e.g., eight crackers placed in bucket A, one cracker placed in bucket B, one more cracker placed in bucket A) merits future investigation.

In contrast to their performance in Condition AABA, infants succeeded in this Condition ABAA, with 13 of 16 choosing to approach the first bucket, which was the site of the reupdating attempt ($p < .05$, two-tailed sign test). There were no effects of sex or side of presentation. At the very least, infants' performance in Condition ABAA suggests that attempting to reupdate a representation within a scene does not entirely disrupt the ability to make an ordinal comparison. Thus, although infants appeared unable to maintain the initially stored representation of a bucket's contents after attempting to reupdate that representation, they successfully formed a new representation of objects at that same location.

Interestingly, within the age range we investigated (9 months; 16 days–13 months; 2 days across Experiments 1–3), we found no evidence for developmental change in infants' reupdating ability. When we collapsed across the two conditions requiring reupdating (Conditions ABA and AABA) and asked whether success varied as a function of age, we observed no tendency for older infants to perform better than younger infants. The average age of the 16 infants who chose the bucket containing the smaller number of crackers was 11 months; 10 days. The average age of the 16 infants who chose the bucket containing the larger number was 11 months; 11 days.

GENERAL DISCUSSION

Previous research suggests that infants can update the contents of working memory to accurately represent arrays of hidden objects, and can compare these representations to determine which contains the greater quantity (Cheries et al., 2008; Feigenson & Carey, 2003; Feigenson et al., 2002; vanMarle & Wynn, submitted). Here, we use the term *updating* to describe the act of dynamically altering a representation of an array to incorporate changes that are made outside of immediate perceptual experience. The research reported here demonstrates a surprising limitation to this ability. Eleven-month-old infants were able to track one versus two hidden objects and to compare these in memory when the items were hidden in direct succession (Experiment 1). However, when required to reupdate a representation of a previously stored array, infants failed, even with numerosities well within their working memory capacity (Experiments 2 and 3). Such reupdating, as in Condition ABA when the one versus two arrays were presented in spatiotemporal alternation, requires the additional step of shifting attention away from the currently attended array to track objects elsewhere, and then returning to alter the representations of the original array. Thus, reupdating requires that a representation remain sufficiently flexible to permit subsequent changes, even after infants have attended to objects elsewhere in the scene. The pattern of success and failure in the six experimental conditions we present here suggests that infants' working memory representations might lack this flexibility.

Of course, reaching this conclusion requires first ruling out other task demands as the source of infants' failures. First, infants' performance pattern cannot be attributed to presentation order (see Figure 2). Their failures do not reflect a primacy effect, as the presentation began on the side that would contain the larger quantity in Condition ABA of Experiment 2 and Condition AABA of Experiment 3, yet infants failed in these. Infants also succeeded in Condition ABB

	Experiment 1		Experiment 2		Experiment 3	
	ABB	AAB	ABA	A(B)AB	AABA	ABAA

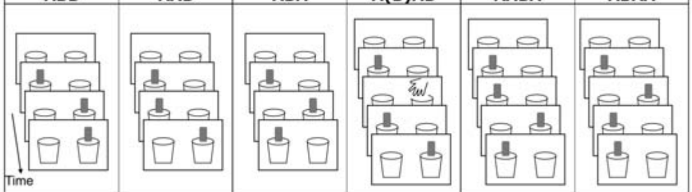

	ABB	AAB	ABA	A(B)AB	AABA	ABAA
Success?	yes	yes	no	yes	no	yes
Last fixation on winning side?	yes	no	yes	no	yes	yes
Total crackers	3	3	3	3	4	4
Total hand movements	3	3	3	4	4	4
Success if last 2 presentations only?	yes	yes	no	no	no	yes
Total time (sec)	8.3	8.2	11.2	9.2	11.7	11.6

FIGURE 2 Presentation descriptors for the six experimental conditions in Experiments 1 through 3.

of Experiment 1 even though the presentation began with the smaller quantity. Nor do infants' failures reflect a recency effect (see Kaldy & Leslie, 2005, for evidence of recency effects in infant working memory), as the presentation ended on the side containing the larger quantity for Conditions ABA and AABA, yet infants failed in these. Therefore, order effects do not explain the overall pattern of infants' performance.

Another possibility is that infants were only able to encode or store the last two presentation events they saw, regardless of the number of crackers involved in each event. Previous research on the development of long-term memory capacity has found that 11-month-old infants successfully remember sequences containing two novel events (Bauer & Mandler, 1992), and 13.5-month-old infants successfully remember sequences containing three events (Bauer & Hertsgaard, 1993). One might worry that 11-month-old infants (the average age we tested) cannot represent sequences involving three events, where an event is bounded by a movement from one attended spatial location (e.g., bucket A) to another (e.g., bucket B). However, this explanation is ruled out by infants' success in Condition A(B)AB, which required integrating representations across four spatially separated events (see Figure 2). Despite the large number of attentional switches imposed by Condition A(B)AB, this condition did not require reupdating because the hand wave that occurred midway between the presentation of the first and second crackers in the first bucket did not require creating a representation of a new object at the second bucket. In this case infants succeeded despite the large number of attentional switches and large number of individual presentation events. We suggest this is because no reupdating was required.

A third concern is that infants succeeded in the original one versus two comparison task by Feigenson and colleagues (2002) but failed in the present reupdating conditions because the reupdating conditions were longer in total presentation duration, thereby allowing infants' memories to decay. This interpretation is ruled out by infants' success in Condition ABAA, which lasted longer than the reupdating sequence in Condition ABA, and also by a previous two versus three cracker comparison that required no reupdating but involved a longer total presentation duration than Condition ABA (Feigenson et al., 2002).

In some ways, the failures we report here may be reminiscent of the A-not-B failures observed in 7- to 12-month-old infants (e.g., Diamond, 1985; Piaget, 1954; Smith, Thelen, Titzer, & McLin, 1999; Wellman, Cross, & Bartsch, 1987). In these striking A-not-B failures, despite seeing an object hidden before their very eyes, infants fail to reach for the object at location B after they have already retrieved it several times at location A. Although there are some similarities between the A-not-B task and our reupdating task, such as switching attention between two locations and failing to represent a hidden object, there are also some important differences. For infants to perseveratively search at location A in the A-not-B task, they must first reach multiple times to location A. In our paradigm, each infant only received one trial and therefore made only one behavioral choice. Hence perseveration of the type seen in A-not-B tasks was intentionally ruled out by our reupdating task. Furthermore, even if one assumes that perseveration is possible without having performed a repeated motor response, perseveration in our task would predict failure in Condition AAB (two crackers hidden at the first location, then one cracker hidden at the second location); predictions for the other conditions in which there were multiple switches of attention are unclear. However, infants succeeded in Condition AAB, and previous experiments have found no differences between conditions in which the larger number of crackers was placed first or second (Feigenson & Carey, 2005; Feigenson et al., 2002). For these reasons, we feel that it is unlikely that the A-not-B error is responsible for the performance pattern we observed.

Having ruled out a variety of ancillary factors as the source of infants' performance pattern, we can now ask why reupdating is so hard. It is worth noting that integrating working memory representations across separate events is difficult for adults as well as for infants. For example, when shown a simple dot array followed approximately 2 sec later by a different dot array, adults can compare the two arrays in memory. However, they are unable to form a single new representation that integrates across the two arrays (Jiang & Kumar, 2004; Jiang et al., 2005). Integrating across sequential representations is exactly what is required by our reupdating conditions, as veridical knowledge that there are two crackers in the first bucket can only be reached by combining representations of two distinct presentation events, each of which involved just a single cracker. Furthermore, in the rapid visual presentation task just described, adults' memory is better for the second array in the sequence than for the first (Jiang & Kumar, 2004). This effect might be related to infants' performance in our Conditions AABA and ABAA, where infants' memory for the original object array was destroyed or overwritten (Condition AABA), but their memory for the newly presented objects at that same location was intact (Condition ABAA).

These parallels between adults' and infants' reupdating performance are suggestive, but should be considered with caution because of the difference in time scale. Jiang and colleagues presented adults with array sequences lasting less than 3 sec—durations typically thought to engage visual short-term memory. In contrast, we presented infants with sequences lasting more than 10 sec—durations more consistent with engagement of working memory. Nonetheless, because the point of temporal division between these two memory stores is not always clear (Noles, Scholl, & Mitroff, 2005; Palmer, 1999), considering these parallels might be useful.

Moreover, adults also have difficulty reupdating in a task that more clearly taps working memory. Garavan (1998) presented adults with sequences of triangles and rectangles and asked them to keep a running count of the number of items in each category. Adults were slower when they had to switch between the two counts and then increment (i.e., when they had to reupdate) relative to updating the same count twice in succession. This cost persisted even when controlling for the cost of simply switching attention between the two counters. That is, reupdating (switching counters and then incrementing) hurt performance more than switching and incrementing by zero (Kessler & Meiran, 2006; Oberauer, 2003). These studies show that although adults do not exhibit a complete failure to reupdate as the infants in our experiments did, they too find reupdating more difficult than updating.

That reupdating is difficult for both infants and adults is consistent with the suggestion that the contents of working memory are selectively attended, with one or two items held in a state of increased availability for processing (Cowan, 2001; Garavan, 1998; Jonides et al., 2008; McElree & Dosher, 1989; Oberauer, 2003). For example, in the experiments by Garavan (1998), adults were able to hold two counters in working memory, but only one of the counters was maintained in the focus of attention at any given time. Adults were fast at incrementing that counter, but showed a reaction time cost when they had to switch their focus of attention to the other counter to increment it. Analogously, infants in our task appeared able to add crackers to a representation of a hidden array when that array was currently being held in the focus of attention (Conditions ABB, AAB, A(B)AB, and ABAA). Infants were also able to create a new counter while already maintaining one in working memory—forming a representation of an array at the second bucket (Conditions ABB, AAB, A(B)AB, ABAA). However, infants were unable to return to the representation of the first array and reupdate it when it was no longer in the focus of attention (Conditions ABA and AABA). It remains an open question why the infants in our task appeared completely unable to reupdate, whereas adults could do so but at a reaction time cost (Garavan, 1998; Kessler & Meiran, 2006; Oberauer, 2003). This difference in the magnitude of the effect of reupdating on performance might have been due to task differences. Alternatively, infants might genuinely have more difficulty switching the focus of attention than adults do. Many studies have implicated the prefrontal cortex as a key locus for controlling and coordinating switching within working memory (e.g., D'Esposito et al., 1995). Infants have notorious difficulty in tasks involving this type of executive control (e.g., Diamond & Doar, 1989); this difficulty is typically attributed to the protracted development of prefrontal cortex (Kanemura, Aihara, Aoki, Araki, & Nakazawa, 2003). Maturation of prefrontal cortex might contribute to success at reupdating.

Additionally, the nature of the reupdate required by our task might differ from that in previous work with adults. Adults have typically been instructed to mentally increment alternating numerical counters (Garavan, 1998; Kessler & Meiran, 2006; Oberauer, 2003), a process that might involve an alteration to an already existing memory representation rather than the formation of a completely new item in memory. In contrast, the reupdating in our task required the addition of an entirely new object representation each time the experimenter placed another cracker in either bucket, and previous work suggests that each cracker is maintained as a separate object representation in working memory (Feigenson et al., 2002). The difficulty in our task might arise from the need to create a new object representation, rather than just altering an existing one. This account raises the possibility that infants might be more successful when performing a reupdate involving the subtraction of an object from an array, rather than the addition of an object to an array. However, preliminary work in our laboratory suggests that when infants see one cracker placed in bucket A, one cracker placed in bucket B, and then one cracker subtracted from bucket A, they choose at chance. Hence, reupdating might be hard for infants regardless of the nature of the reupdate.

Infants' difficulty with reupdating might also be related to another working memory computation—that of binding individual memory representations into sets (sometimes referred to as *chunking*). Recent research has shown that infants can sometimes overcome the three-item limit of working memory and remember more total items if they treat individual objects as members of sets (Feigenson & Halberda, 2004, 2008). This type of hierarchical reorganization has long been known to increase adults' memory capacity (e.g., Chase & Simon, 1973; Ericsson, Chase, & Faloon, 1980; H. A. Simon, 1974). Consider infants' success in the two versus three condition of the cracker choice experiments by Feigenson and colleagues (Feigenson et al., 2002). When given this choice, infants successfully approached the greater quantity despite the fact that the total number of crackers presented (five) exceeded the three-item limit on working memory. This result is consistent with infants having conceived of the crackers in each bucket as forming a set—rather than being constrained to remembering three objects in total, infants appeared constrained to remembering three objects per set. Viewed in this light, the results reported here suggest that infants can only bind object representations into a set when that set is held in the current focus of attention. Once items have been bound into a set, infants might not be able to add any further items to the set, leading to the failure we observed in Conditions ABA and AABA. Further work in our lab is ongoing to determine whether infants' difficulty with reupdating is confined to situations involving set binding or chunking, or whether it applies more broadly across a range of working memory tasks.

To summarize, our results confirm previous findings that 11-month-old infants can maintain representations of hidden object arrays across multiple spatial locations and can compare these in memory. To do so, infants in our task needed to update their working memory representations of presentation events that unfolded over time. Infants' success at this demonstrates that, even early in development, working memory provides a workspace to keep track of an ever-changing environment. However, infants' working memory representations also exhibited a striking limitation: Infants were unable to reupdate representations of arrays that were not held in the current focus of attention. These findings shed light on both the capacities and the constraints of working memory throughout development, and in so doing provide some insights into a foundational mental storage system.

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