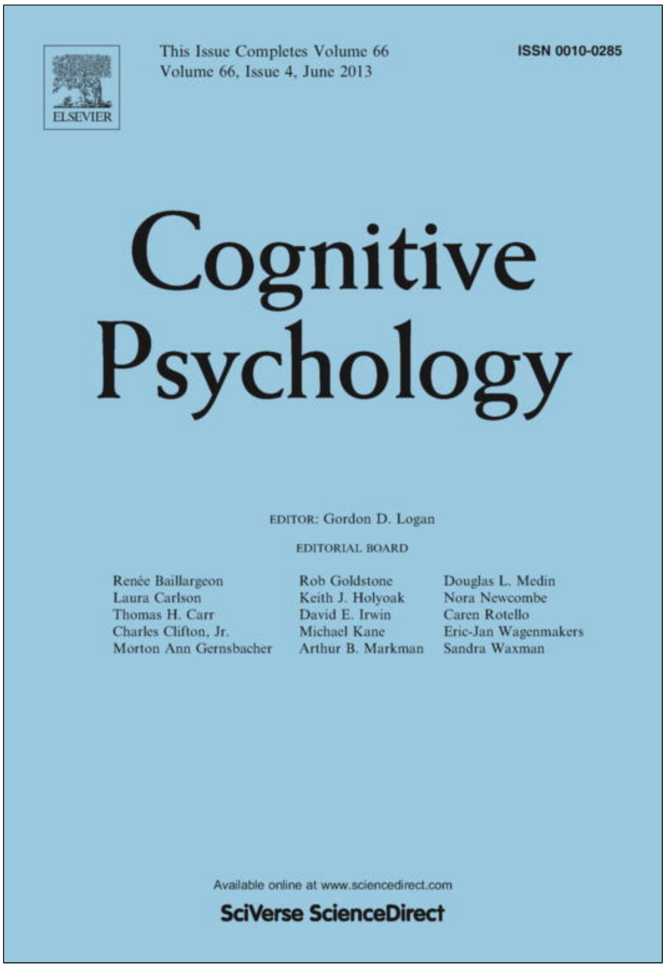
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What's the object of object working memory in infancy? Unraveling 'what' and 'how many'

Melissa M. Kibbe [a,b,*], Alan M. Leslie [b,1]

[a] Johns Hopkins University, Department of Psychological and Brain Sciences, 3400 N Charles St., Baltimore, MD 21218, United States
[b] Rutgers University, Department of Psychology and Center for Cognitive Science, 154 Frelinghuysen Rd., Piscataway, NJ 08854, United States

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ABSTRACT

Infants have a bandwidth-limited object working memory (WM) that can both individuate and identify objects in a scene, (answering 'how many?' or 'what?', respectively). Studies of infants' WM for objects have typically looked for limits on *either* 'how many' *or* 'what', yielding different estimates of infant capacity. Infants can keep track of about three *individuals* (regardless of identity), but appear to be much more limited in the number of specific *identities* they can recall. Why are the limits on 'how many' and 'what' different? Are the limits entirely separate, do they interact, or are they simply two different aspects of the same underlying limit?

We sought to unravel these limits in a series of experiments which tested 9- and 12-month-olds' WM for object identities under varying degrees of difficulty. In a violation-of-expectation looking-time task, we hid objects one at a time behind separate screens, and then probed infants' WM for the shape identity of the penultimate object in the sequence. We manipulated the difficulty of the task by varying both the number of objects in hiding locations and the number of means by which infants could detect a shape change to the probed object. We found that 9-month-olds' WM for identities was limited by the number of hiding locations: when the probed object was one of two objects hidden (one in each of two locations), 9-month-olds succeeded, and they did so even though they were given only one means to detect the change. However, when the probed object was one of three objects hidden (one in each of three locations), they failed, even when they were

* Corresponding author at: Johns Hopkins University, Department of Psychological and Brain Sciences, 3400 N Charles St., Baltimore, MD 21218, United States. Fax: +1 (410) 516 4478.
E-mail addresses: kibbe@jhu.edu (M.M. Kibbe), aleslie@ruccs.rutgers.edu (A.M. Leslie).
[1] Fax: +1 (732) 445 6715.

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given two means to detect the shape change. Twelve-month-olds, by contrast, succeeded at the most difficult task level.

Results show that WM for 'how many' and for 'what' are not entirely separate. Individuated objects are tracked relatively cheaply. Maintaining bindings between indexed objects and identifying featural information incurs a greater attentional/memory cost. This cost reduces with development. We conclude that infant WM supports a small number of *featureless* object representations that index the current locations of objects. These can have featural information bound to them, but only at substantial cost.

1. Introduction

Classical blank-slate, bottom-up theories of learning entail that space and, therefore objects, are experienced initially as two-dimensional. Piaget (1955), for example, rested the entire developmental period of infancy upon an inability to represent the continued existence of objects that become hidden behind other objects or surfaces. The 1980s, however, saw a sea change in which developmentalists broadly came to accept that vision is inherently organized to represent three spatial dimensions (3-D) and that even young infants can represent hidden objects. The infant literature came to focus on the rich top-down expectations concerning the physical properties of objects that infants bring to bear on learning about how objects in a 3-D world behave (e.g., Baillargeon & DeVos, 1991; Baillargeon, Spelke, & Wasserman, 1985; Kellman & Spelke, 1983; Spelke, 1990).

Into the bottom-up vs. top-down debate over the origins of object cognition, Leslie, Scholl, and colleagues argued for a third intermediate-level source of constraints that structure attention to objects and provide a place for bottom-up and top-down constraints to meet (Leslie, Xu, Tremoulet, & Scholl, 1998; Scholl & Leslie, 1999). They proposed a model for how, in infancy, objects get associated with 3-D locations and featural information gets associated with objects. The idea is that the object concept in infants is supported by a visual indexing system, similar to that studied in adults under various headings (e.g., Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989; Trick & Pylyshyn, 1994). Object indexes are automatically initiated as objects come into view and grab attention, and then act as pointers to those objects as the objects move around. These pointers themselves contain no featural information about the objects they index; but they "stick" to individual objects as the objects move through 3-D space, and continue to stick even if objects go out of view. Once established, an index can be assigned bottom-up featural information, which needs to be bound *to* the index.

Object-indexing theory makes a key distinction between *individuation* of objects and *identification* of objects. Objects are *individuated* when separate indexes are assigned to those objects. Object indexing can be initiated either by spatiotemporal properties (e.g., location) or by featural properties (e.g., color). However, successful individuation does *not* require that featural information be bound to an index. Furthermore, even if featural information *is* bound to an assigned index, that information may be lost subsequently without preventing continued tracking of the object (Kibbe & Leslie, 2011). However, in order to successfully *identify* a specific object, features must not only be bound to individuals but those bindings must also be maintained over time.

To illustrate the distinction between individuation and identification, imagine you are watching a red car and a blue car drive into two separate tunnels. If you have *individuated* the two vehicles, you should expect that some one *thing* would emerge out of each of the tunnels (and not 2 things from one tunnel, or 3 things total, for example). If you have *identified* the two vehicles, you should expect a red car to drive out of the first tunnel and a blue car to drive out of the second tunnel (and not the other way around). If you have not successfully identified the two vehicles, binding the relevant featural information to the individual in each location, it would not matter to you whether they each emerged from the wrong tunnels (e.g., the red car emerging from the second tunnel rather than the first) or whether two new vehicles (say, a motorcycle and a tractor trailer truck) emerged from the tunnels.

The importance of making the distinction between individuation and identification in infants is apparent when considering the series of now classic experiments conducted by Xu and Carey (1996). They found that 12-month-olds, but not 10-month-olds, could individuate objects by property/kind information alone when they saw two objects that appeared alternately from either side of a screen on the same spatiotemporal trajectory (both age groups could individuate the objects given both spatiotemporal and featural cues). Xu and Carey's initial evidence suggested that infants needed to have conceptual (that is, top-down) knowledge of the objects in order to individuate them by feature alone.

However, an alternative possibility is that once a feature is used to individuate an object, it does not necessarily have to be bound to that object. Thus, when a featurally distinct object appears to move on the same spatiotemporal trajectory, it will not be individuated as a separate object. That is, *individuated* need not necessarily be *identified*. Indeed, in a task where infants had to keep track of objects in different locations, Tremoulet, Leslie, and Hall (2000) showed that the features used to initiate an object representation are not necessarily bound to that object.

1.1. Individuation and identification in infant working memory

Making the distinction between individuation and identification is essential when studying the development of working memory (WM) in infants. This is because there have been primarily two lines of research that have investigated how WM develops: one line has focused on *how many* items infants can keep track of in WM, emphasizing number of individuals, while another line of research has asked *what* infants can recall about objects, emphasizing featural identity. These two lines of research, separately tapping WM for *how many* and for *what*, have yielded different estimates of the limits of infants' WM.

1.1.1. Limits on 'how many'

Following Wynn (1992) it became apparent that infants were able to keep track of more than one object hidden in a single location. They could even update their representation of what was hidden at that location, even when the updating events were never visible. However, there are limits to these abilities. In Feigenson, Carey, and Hauser's (2002) foraging task, 10- and 12-month-old infants watched as sets of graham crackers were placed in each of two different opaque containers. The sizes of each set varied, but one location always had more than the other location. They found that infants preferentially crawled to the container with more crackers, suggesting that they were able to represent the number of items at each location and compare those two representations. However, infants only crawled to the container with the greater number of crackers when the number of crackers in either of the containers did not exceed 3. For example, infants preferentially chose 3 crackers to 1, but were at chance when the choice was between 2 and 4 crackers (they could, however, distinguish 4 from 0 crackers; Feigenson & Carey, 2005).

This limit of about three items also appears in other tasks. Feigenson and Carey (2003) obtained similar results with a manual search task using a single location. Twelve- and 14-month-old infants watched as an experimenter placed 1, 2, 3, or 4 identical table tennis balls inside of a box whose contents were hidden from the infant by a flap. The infant was prompted to remove one or more of the balls, at which point the infant was allowed to search in the box to retrieve any balls that were left (unbeknownst to the infant, the experimenter held back any of the remaining balls so that the infant could not reach them). Feigenson and Carey (2003) found that infants searched longer when there were balls remaining in the box, but only up to set size 3. At set size 4, infants did not search longer than when the box was empty, suggesting that infants' WM representation of the array fell apart after the limit of 3 was reached. Further, the 3-item 'how many' limit appears robustly whether infants are tracking individuals or sets of individuals (Zosh, Feigenson, & Halberda, 2011; see Feigenson & Halberda, 2004, 2008; Moher, Tuerk, & Feigenson, 2012, for evidence that infants can use chunking strategies to help overcome individual item limits).

Leslie and Káldy (2007) point out that the 'how many' limit appears not to change across the second half of the first year. Indeed, the limit is similar to the limits on WM found in adults using a variety of methods (e.g., Cowan, 2001; Luck & Vogel, 1997; Pashler, 1988; Wheeler & Treisman, 2002). However, it is important to note that, unlike the infant studies described in this section, studies of adults' WM limits generally test recall for the *identities* of objects in the array to obtain the estimate of capacity at about 3 or 4 items. Let us now consider studies examining infants' WM for object identities.

1.1.2. Limits on 'what'

The studies described in Section 1.1.1 showed a limit to infants' WM of about three individuals that does not seem to develop across the first year of life. The picture looks rather different for infants' recall of featural information.

For example, Káldy and Leslie (2003, 2005) asked whether infants could keep track of multiple object identities when their memory was probed for each object separately. In their task, infants were familiarized with two objects that differed only on a single dimension, either shape (a triangle and a disk) or color (red and green). On each familiarization trial, the order of presentation and the positions of the objects were counterbalanced so that no long-term bindings between shape and location could be formed. During test trials, the objects were hidden one at a time, and then *one* of the objects was revealed to have changed (unexpected outcome) or stayed the same (expected outcome). Thus, they could test infants' memory for each item separately, either by revealing the most recently hidden item (easier to remember because it was hidden last) or the first-hidden item (more difficult to remember because after it was hidden infants' attention was drawn to the intervening object).

Using this methodology they found that 6.5-month-old infants were only able to recall the shape of the easier-to-recall object (Káldy & Leslie, 2005), while 9-month-olds could recall the shape of both objects (but not their colors; Káldy & Leslie, 2003). Thus 6.5-month-olds appear to have a WM span of only one object shape, while 9-month-olds have a WM span of (at least) two. These findings suggest that WM for object *identities* increases across the second half of the first year of life.

1.2. Unraveling the limits

The studies described above point to two distinct limits in infant WM. One limit applies to how many *individuals* infants can hold in WM; this limit appears to be around three items and remains stable across the second half of the first year. The second limit applies to the number of *identities* infants can hold in WM; this limit appears to increase across the second half of the first year.

The possibility of there being distinct memory limits for individuals and their identities is in keeping with the object-index structure put forth by Leslie and colleagues (Leslie et al., 1998; Scholl & Leslie, 1999). For example, it may be that individuated objects are tracked relatively cheaply while identifying information about each object may be costlier to maintain. If this is so, increasing the number of locations in which infants have to track objects may result in less featural information retained from each object. That is, as infants have to allocate more attentional resources to tracking the individuals, they have fewer resources left for maintaining bindings between feature and object over time. Thus, limits on 'how many' would remain about the same while limits on 'what' would be more severe.

Kibbe and Leslie (2011) recently demonstrated the above effect in 6-month-olds. Infants who entirely forgot the identity of a hidden object nevertheless retained an inkling of its existence. In a looking-time study, infants were familiarized with a disk and a triangle placed on opposite sides of a stage. During test trials, the objects were hidden one at a time behind different screens, and after hiding the second object, the screen where the first object had been hidden was removed. Infants then saw the expected shape, the unexpected other shape, or the empty stage. Bayes Factor analysis showed that although the infants did not notice when the object changed shape (null hypothesis supported), they were surprised when it vanished. These two findings show that infants can represent an object *without* its uniquely identifying perceptual features.

Kibbe and Leslie's (2011) results show that the limit on 'how many/where' and the limit on 'what' are separable; 6-month-old infants recalled an individual even when they could not recall its identity. However, it is unclear how, if at all, these limits interact. Does infant WM for 'what' become even more limited if infants are asked to recall more items? Or are the limits completely separate, such that no matter how many individuals infants are asked to recall, the number of identities they can recall remains fixed? Further, does the interaction between the two limits change with development?

1.2.1. Three dimensional objects in motion in a 3-D world vs. blinking 2-D stimulus arrays

In order to unravel the cognitive architecture underlying WM for 'how many' and for 'what', we must first define the problem space that infants face in the studies described above. In the classic studies of the object concept in infants, experimenters typically use real objects and 3-D scenarios in which those objects are physically hidden and revealed. In studies of adult visual WM, however, the stimuli are typically two-dimensional and appear and disappear instantaneously. For example, adults may be shown an array of colored squares, which then disappear, and then reappear; adults may then be tasked with reporting whether one of the squares has changed color (e.g., Luck & Vogel, 1997).

Ross-Sheehy, Oakes, and Luck (2003), adapted this type of change detection task for young infants. The display consisted of two screens. On each screen was 1, 2, or 3 colored squares which appeared for a short interval, disappeared for a short interval, and then reappeared. On one screen, the colors of the squares always remained the same. On the other screen, the colors changed. If infants were able to retain the color information across the short retention interval, they should prefer to look at the changing, and thus more interesting, screen. Ross-Sheehy et al. found that infants 6.5 months of age preferred the changing stream at set size 1 only; by 10 months, infants preferred the changing stream even at the largest set size. In a follow up study, Oakes, Ross-Sheehy, and Luck (2006) asked whether infants could bind features to location. In that study, set size was held constant at 3, and squares in the changing stream swapped colors. Six-and-a-half-month-olds did not prefer the changing stream, while 7.5-month-olds did (see Oakes, Hurley, Ross-Sheehy, & Luck, 2010, for similar findings for location changes rather than color changes).

Change-detection tasks that use 2-D blinking displays and those that use real 3-D objects and natural occlusion show converging evidence that infants' memory for object identities is limited, and that it develops across the second half of the first year of life (Kibbe & Leslie, 2011; Káldy & Leslie, 2003, 2005; Oakes et al., 2006; Ross-Sheehy et al., 2003). However, it is likely that these different types of task are tapping somewhat different sets of cognitive processes (Wang & Baillargeon, 2008). While 3-D physical objects persist over space and time, 2-D arrays blink in and out of existence or appear to implode, specifying the non-permanence of the objects (Michotte, 1963). Studies using multiple object tracking (MOT) have shown that neither infants (Cheries, Feigenson, Scholl, & Carey, in preparation) nor adults (Scholl & Pylyshyn, 1999) track objects that blink in and out of existence or appear to implode, and objects that break apart or lose cohesion fail to illicit object indexes in infants (Cheries, Mitroff, Wynn, & Scholl, 2008). When adult participants were given visual cues to the persistence of 2-D objects (e.g., if a colored square moved in and out of occlusion on a defined spatiotemporal trajectory), change detection performance was significantly better than when those cues were absent (Flombaum & Scholl, 2006). Neural evidence from infants, adults, and rhesus macaques suggests that objects that become occluded, either by moving behind an occluder or by having the occluder move in front, are represented in inferior temporal cortex (Kaufman, Csibra, & Johnson, 2003; Woloszyn & Sheinberg, 2009), whereas objects that blink in and out of existence are represented in inferior intraparietal sulcus (Xu & Chun, 2006). Hollingworth and Rasmussen (2010), using a behavioral method that required both object tracking (after Kahneman et al., 1992) and visual working memory (after Luck & Vogel, 1997), found that the object-indexing framework and visual working memory are related but are not identical.

Thus, we argue that scenarios involving 3-D objects and occlusion tap infants' object-indexing system. Infants must track the objects as they go in and out of view, and, if possible, maintain the featural properties of those objects by binding their properties to the corresponding indexes.

1.2.2. The methodological problem of sampling

Infant limits on memory for 'what' can only be determined accurately by addressing the sampling problem. Because WM experiments often give infants multiple ways to succeed, infant limits may be even more severe than has appeared hitherto. For example, in Káldy and Leslie's (2003) study, which explicitly addressed sampling by testing infants' recall of the shape in each location separately, there is still a confound that was not eliminated. Infants' WM was tested for the harder-to-recall shape by showing them either the expected outcome (the original, harder-to-recall shape) or the unexpected outcome of the shape that was hidden *last*, and was thus easier to recall. This aspect of the experiment introduces a confound that makes it difficult to conclude definitively that 9-month-olds are able to recall the shapes of both objects. It is possible that infants' longer looking at the unexpected outcome is driven not by an identity change to the object at the harder-to-recall location, but by a *location* change of the object at the easier-to-recall location. That is, infants are surprised when they see the easily remembered object in the wrong location (but may have forgotten the shape of the object that *should* have been there). Thus, infants do not necessarily have to remember the specific shape of the harder-to-recall object. All they have to do is individuate the two objects, but remember the identity of only one of those objects: the one that was hidden last and was thus easier to recall.

1.3. The current studies

The current studies test 9- and 12-month-olds' WM for identities under varying degrees of difficulty. We varied both the number of objects and the number of hiding locations infants had to track. At the same time, we varied the difficulty of the identity-recall task by controlling for the sampling problem described in Section 1.2.2. We predict that, if WM for 'what' and 'how many' are independent, then increasing the number of locations in which infants have to track objects should have no effect on their WM for 'what'. However, if infants have to keep track of what went where by maintaining bindings between feature and object, then increasing the number of locations in which infants have to track objects should tax infants' object indexing system. As infants observe each new hiding event, their attention is diverted from maintenance of current feature bindings to forming a representation of the newly hidden object. Infants would be able to recall fewer identities because bindings between feature and object are harder to maintain.

In experiment 1, we designed a modification of the violation-of-expectation (VOE) method used by Káldy and Leslie (2003). We introduced a third shape and a third hiding location for that shape; we then tested infants by swapping the second-hidden object for the object that was hidden *first* rather than the object that was hidden *last*. This prevents infants from simply noticing that the last object they had seen had switched locations and forces them to remember the specific identity of the object hidden at the second location. Both experiment 1 and Káldy and Leslie (2003) test infants' memory for the shape hidden second-to-last, but in experiment 1 infants can no longer rely on their memory representation for the easier-to-recall (last-seen) object in order to succeed at the task.[2] Thus, we are calling this type of swap scenario a *difficult swap*. The swap is *difficult* because, on each trial, infants are only given one means of detecting an inconsistency at a given location: they must remember the specific shape of the object that was hidden in that location originally. By contrast, an *easy swap* is one in which infants are given more than one means of detecting an inconsistency at the location: they could either remember the specific identity of the object that was hidden at that location, and notice that it changed identities, or they could remember the specific identity of the object hidden most recently in the easier-to-recall location, and notice that it changed locations. Káldy and Leslie's (2003) experiments would fall into the category of *easy swap* under our criteria. Our terminology of "hard" vs. "easy" swaps reflects our assumption that a detection task becomes easier the more ways there are to arrive at a correct solution.

Here, we asked whether 9-month-olds were able to recall the second shape with a three-location task that blocks a strategy of simply remembering the shape of the easiest-to-remember (last-hidden) object (a *difficult swap*).

2. Experiment 1: Three locations, difficult swap

2.1. Method

2.1.1. Participants

Participants were 24 healthy full-term infants (13 females) between 34.3 and 43.6 weeks of age (mean = 38.4 weeks, SD = 3 weeks) who were tested at Rutgers University. An additional three infants were excluded due to fussiness (2) or experimenter error (1). Participants were recruited from local towns around Rutgers University through phoning lists and advertisements, and received a

[2] None of the experiments described in this paper explicitly test infants' memory for the easier-to-recall, last-seen object. However, it is reasonable to assume, based on previous work, that if infants are able to recall the shape of an object hidden first (or second), they are able to also recall the shape of the object hidden last because it is easier to remember (Káldy & Leslie, 2003, 2005; Leslie & Chen, 2007). Therefore, discussions of the results of the experiments in this paper will make this assumption whenever applicable.

reimbursement and a small gift. Infants were divided evenly into two groups, where each group saw one of two outcomes detailed below ($n = 12$ per condition, between-subjects design).

2.1.2. Design

Infants were familiarized with three objects, a disk, a triangle, and a square, placed on an empty stage. The location of placement of the three objects was alternated from trial to trial, so that each object appeared equally often in each location. Objects were presented right-to-left or left-to-right, alternating on each trial (see Fig. 1). Following familiarization, three screens were placed on the empty stage. Continuing the alternating-position placement, the three objects were placed on the stage, one in front of each screen, and then placed one at a time behind their respective screens.

Once hidden, the screen in front of the *second*-hidden object was removed to reveal one of two possible outcomes: the object that had been hidden there originally (*control* condition); or the object that had been hidden *first* (*difficult swap* condition), see Fig. 2.

2.1.3. Apparatus

Infants were seated on a caregiver's lap in a booth enclosed by blue curtains, about 91 cm from a white puppet stage with a light blue base (95 × 48 × 56 cm). Stimuli consisted of three wooden shapes painted red, a triangle (base = 10.15 cm, height = 11.4 cm), a disk (diameter = 10.15 cm), and a square (9.5 × 9.5 cm), and three gray foam-core occluders (each 17.75 × 17.75 cm). During the experiment, shapes were placed at the front of the stage (99 cm from the infant; 6° visual angle) and then moved to the back of the stage (138 cm from the infant, 4° visual angle). During test trials, occluding screens were placed about 133 cm from the infant. A yellow curtain could be raised to cover

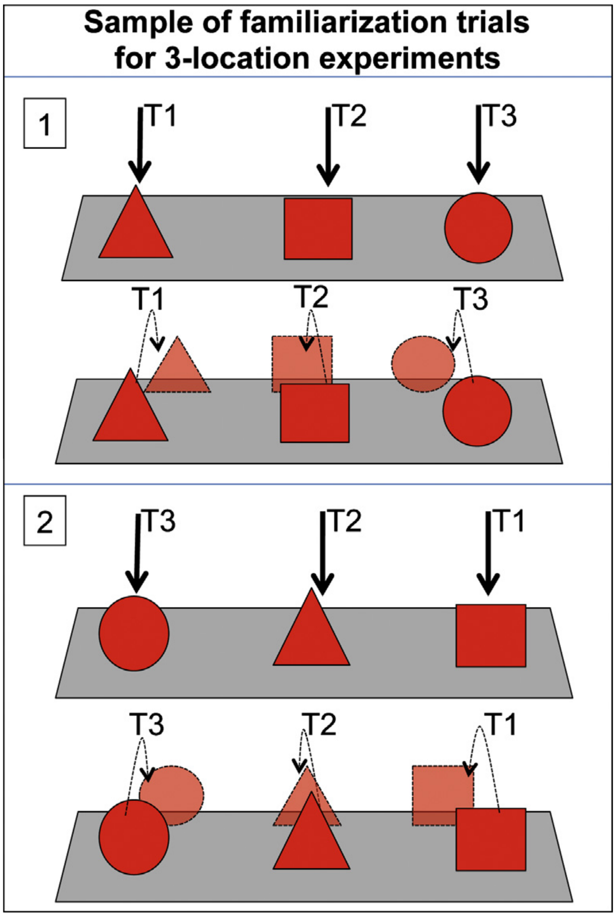

Fig. 1. Two sample familiarization trials used in the 3-location experiments (experiments 1, 3, and 4). The location of each shape and the order in which the shapes appeared were counterbalanced across familiarization trials. Shapes were always presented right-to-left or left-to-right, alternating across trials. Each infant saw four familiarization trials.

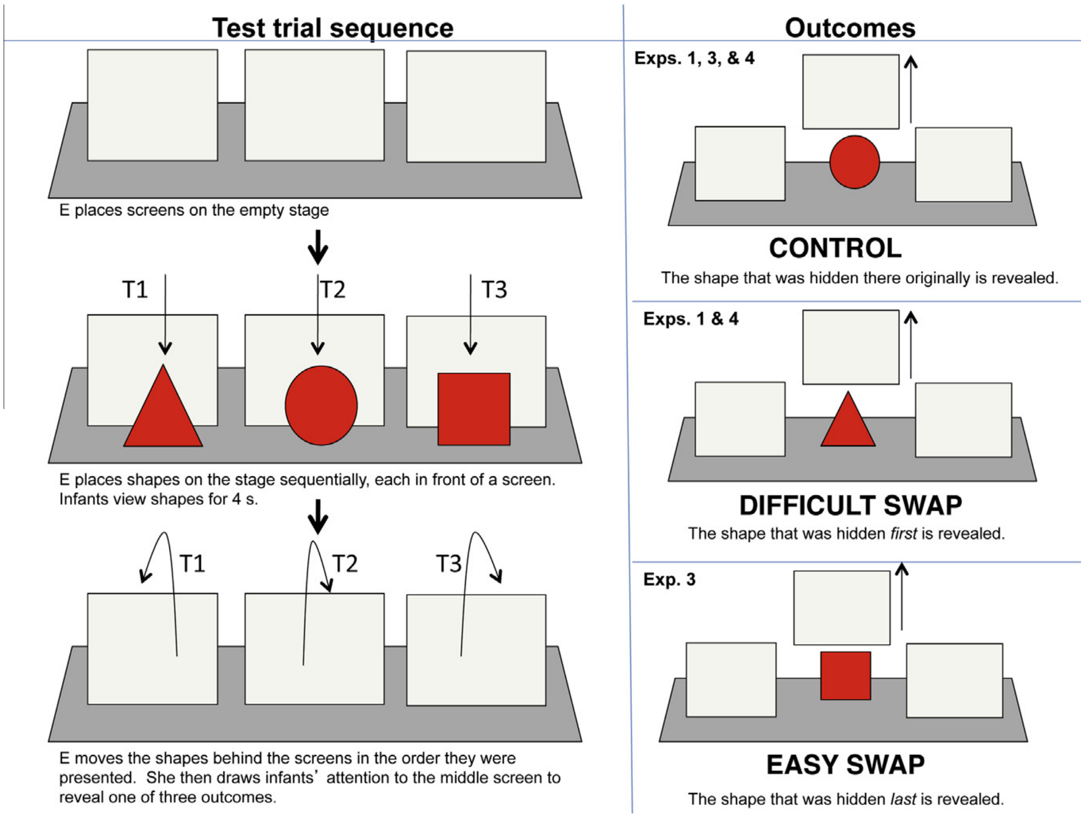

Fig. 2. Trial sequence for 3-location experiments (experiments 1, 3, and 4). The experimenter, E, always hid shapes from right-to-left or left-to-right, and probed infants' memory for the middle location by lifting the screen in that location and revealing one of the possible outcomes. In the *difficult swap* condition (experiments 1 and 4, middle right panel), infants saw the shape that was hidden *first* appear in the probed location. In the *easy swap* condition (experiment 3, bottom right panel), infants saw the shape that was hidden *last* appear in the probed location. In the *control* condition (experiments 1, 3 and 4, top right panel), infants saw the shape that had been hidden in the probed location.

the stage or lowered to reveal the stage. The stage was illuminated by two lights suspended just above the stage, which turned on at the beginning of each trial and turned off at the end of each trial.

2.1.4. Procedure

At the beginning of the experiment, the experimenter drew infants' attention to the front and back center and corners of the stage by jingling bells she wore around her wrist, so that an observer, who was hidden from the infants' view and who would be recording the infants' looking time, could get a sense of the individual infants' eye positions relative to the stage.

2.1.4.1. Familiarization. Over the course of four familiarization trials (see Fig. 1), the experimenter placed three shapes one at a time on the front of the empty stage. After 4 s, she moved the shapes one at a time to the back of the stage in the same order in which they were placed initially. Infants were allowed to view the shapes for 8 s, after which the experimenter raised a curtain covering the viewing area to end the trial. Shapes always appeared either right-to-left or left-to-right, and the location of each shape was alternated across trials so that infants could not form any long-term associations between a shape and a location. There was no occlusion during familiarization trials.

2.1.4.2. Test trials: Three locations, difficult swap. There were four test trials. Before the test trials began, the caregiver was instructed to close his or her eyes. At the beginning of each of the test trials, the experimenter placed three screens toward the back of the empty stage, one directly in the center and the other two on either side of the center screen. She then placed the three shapes one at a time on the front of the stage; the shapes were placed starting from the opposite direction as in the previous trial, and appeared in different locations than in the previous trial. After 4 s she hid the shapes one at a time each behind their respective screens in the same order in which they were placed on the stage initially. The experimenter then drew the infants' attention to the *center* screen (occluding the second-hidden object) by jingling the bells around her wrist. She then raised that screen to reveal one of the two outcomes: infants either saw the shape that was hidden there originally (*control* outcome) or the shape that was hidden *first* (*difficult swap* outcome) (see Fig. 2). Infants were allowed to look at the display until they looked away for 2 consecutive seconds, at which point the stage lights went off automatically and the experimenter raised the curtain covering the stage.

An observer who was blind to outcome (*control* or *difficult swap*) measured infants' looking time during each of the four test trials. An offline observer who was also blind to outcome rescored the infants' looking times to verify the live observer's scores. Reliability, calculated as the mean difference between the live observer's scores and the offline observer's scores divided by the mean of the live observer's scores, was above 0.90. Therefore, the live observer's scores were used for all analyses.

2.2. Results

Analyses were conducted on 96 total test trials. A Trial (4) × Condition (2: *difficult swap* vs. *control*) repeated measures ANOVA showed no within-subjects effect of Trial ($F_{3,66} < 1$, $p = 0.46$, $\eta^2 = 0.038$) and no Trial × Condition interaction ($F_{3,66} < 1$, $p = 0.48$, $\eta^2 = 0.036$). There was also no main effect of Condition ($F_{1,22} < 1$, $p = 0.81$, $\eta^2 = 0.003$). Comparisons of looking times on the first trial only, where effects are often the strongest (Kibbe & Leslie, 2011; Káldy & Leslie, 2003; Káldy & Leslie, 2005), also revealed no significant effect of condition; infants who saw the *difficult swap* outcome did not look longer than infants who saw the *control* outcome ($t_{22} = -0.249$, $p = 0.81$, two-tailed). Mean looking times (averaged first across trials, then across subjects) are plotted in Fig. 3.

2.2.1. Bayes Factor analysis

Infants' pattern of looking in experiment 1 suggested that they did not notice when the second-hidden object changed shape. This led us to want to conclude that the null hypothesis (namely, that infants were unable to recall the shape hidden at the probed location) was true. However, conventional statistics allow us only to *fail to reject* the null hypothesis when the p value is higher than the 0.05 criterion; they do not allow us to *support* the null hypothesis.

Bayes Factor analysis offers an advantage over conventional statistics because it provides a means of obtaining evidence for or against the null hypothesis (Gallistel, 2009; Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayes Factor analysis lets us obtain the likelihood that the same process or

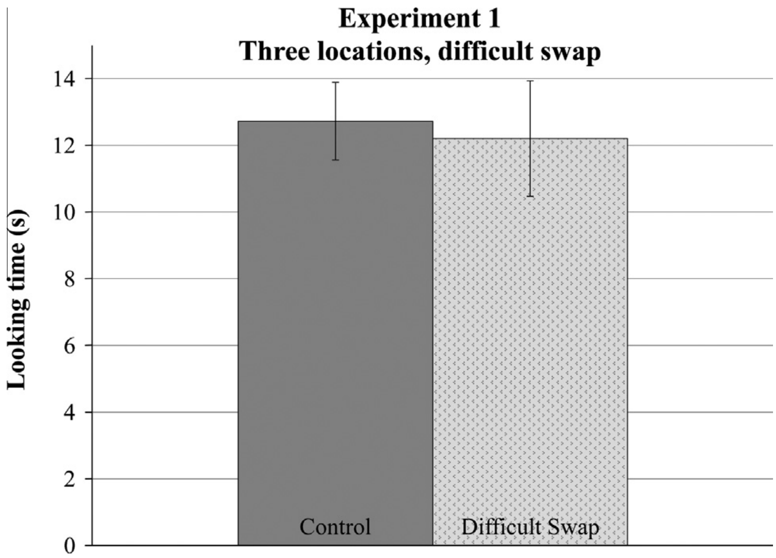

Fig. 3. Nine-month-old infants' looking time scores averaged across trials for experiment 1. Error bars show ±1 SEM.

different processes generated the observed data. In the case of experiment 1, we can find out the odds that infants were unable to recall the shape of the probed object (see Kibbe & Leslie, 2011 for a prior application of this method to infant looking-time data).

Bayes Factor analysis performed on the averaged looking times from experiment 1 revealed odds of 3.63:1 favoring the null hypothesis over the alternative. A Bayes' Factor of 3 or greater indicates a statistical significance equivalent to that of the $p = 0.05$ level in conventional statistics (Gallistel, 2009). Thus, we can *accept* the null hypothesis with confidence; there is no effect of a shape change on infants' looking in experiment 1. In Fig. 4, the theoretical cumulative probability distribution (CDF) functions, obtained by fitting a cumulative Gaussian function to the data, are plotted along with the probability of the data itself. Note that the curves overlap, indicating that the data were indeed generated by similar processes.

2.3. Discussion

In experiment 1, when three objects were hidden individually in each of three locations, infants failed to notice a change to the shape of the object that was hidden second-to-last. This object was equivalent to the object of interest in Káldy and Leslie's (2003) study, in which two objects were hidden individually in each of two locations and the screen hiding the first-to-be-hidden object was removed. Káldy and Leslie (2003) found that infants looked longer when this object unexpectedly changed shape. Why do infants fail to recall the shape of this object in the current study, while succeeding in the previous study by Káldy and Leslie?

One possibility is that infants are not actually able to recall the specific shape of more than one object. Because the shapes in Káldy and Leslie's (2003) study swapped places, infants only had to remember the shape of the easier-to-recall object, and notice that that shape appeared in a new location, in order to succeed at the task. Thus, infants could have no expectations about the shape of the harder-to-recall object and still look longer when the easier-to-recall object is revealed in the wrong location. In experiment 1, when infants were prevented from employing this kind of strategy, they failed.

Another possibility is that the demands of the three-location-difficult-swap task may have been too high for 9-month-olds. In experiment 1, infants were presented with three screened locations and three shapes. It is possible that infants in experiment 1 failed to notice a shape change because keeping track of shapes across three locations infringed on their limited attentional resources, preventing

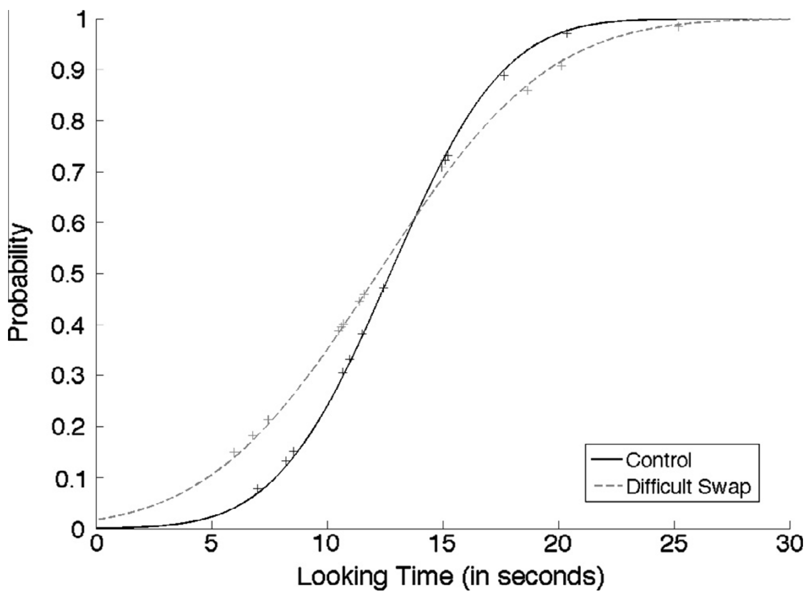

Fig. 4. Cumulative distribution functions (CDFs) show the probability of the looking time data from experiment 1 (crosses) and the theoretical distribution of the data obtained by estimating the maximally likely parameters given the data (lines).

them from maintaining feature bindings across locations. It is crucial to note that infants have no way of knowing which location will be tested and thus have no incentive to allocate resources effectively to only a subset of items in the array. Increasing the number of locations (and indeed, the number of hiding events; see Wang & Baillargeon, 2008) in which infants have to track objects may exceed their attentional limits to such an extent that they are unable to recall items in the array that they previously had no trouble with. Under this possibility, 9-month-olds may be able to recall two shapes, but not when the attentional demands of tracking objects in multiple locations are too high.

In experiments 2 and 3, we test these two possibilities. In experiment 2, we reduced the number of screened locations in which infants had to track objects to two, but used three objects presented two at a time to test infants' memory for the penultimate shape with a *difficult* swap. If 9-month-old infants are in fact able to recall the specific shape of a second object, but in experiment 1 were hampered by the increased number of locations or hiding events, they should look longer at the unexpected shape change in experiment 2, as they did in Káldy and Leslie (2003). Conversely, if infants do not look longer at the unexpected shape change, it would suggest that infants had succeeded in Káldy and Leslie's (2003) study simply by relying on their memory for the easier-to-recall, last-hidden shape, and we can conclude that 9-month-olds' WM for object shape is limited to one shape-object-location binding. In experiment 2 we gave infants only one way to succeed at the task; in order to detect the change to the probed object, infants had to recall its specific shape. Thus, we tested whether 9-month-old infants could indeed recall the shape identities of two objects, or whether they are in fact significantly more limited.

3. Experiment 2: Two locations, difficult swap

3.1. Method

3.1.1. Participants

Participants were 24 healthy full-term infants (10 females) between 34.6 and 42.7 weeks of age (mean = 38.3 weeks, SD = 2.3 weeks). Twenty of these infants were tested at Rutgers University, and 4 were tested at Johns Hopkins University. Infants at Johns Hopkins were recruited through phoning lists. An additional four infants were excluded due to fussiness (1), and equipment malfunction (3). Infants were divided into two groups ($n = 12$), where each group saw one of two outcomes detailed below.

3.1.2. Design

Infants were familiarized to all three shapes (a disk, a triangle, and a square), but only two out of the three shapes were presented at a time. During familiarization trials, infants watched two shapes from the set of three placed sequentially on the front of the stage (e.g., disk and triangle, triangle and square, square and disk). The location of placement of the shapes was alternated from trial to trial, so that each shape appeared equally often in each location and each shape appeared equally often with each of the other shapes (Fig. 5).

Following familiarization, two screens were placed on the empty stage. Two shapes from the set of three were placed on the stage, one in front of each screen. Objects were placed starting from the opposite direction of the previous trial, and so that no shape would appear in the same location as in the previous trial. The objects were then placed one at a time behind their respective screens. Once hidden, the screen in front of the *first* hidden object was removed to reveal one of two possible outcomes: the shape that had been hidden there originally (*control* condition); or the shape that had not appeared on that trial, but to which infants had been familiarized (that is, the third of the three shapes; *difficult swap* condition), see Fig. 6.

3.1.3. Apparatus

For infants tested at both Rutgers University and Johns Hopkins University, stimuli were the same as experiment 1, except only two screens were used. The stage at Johns Hopkins University

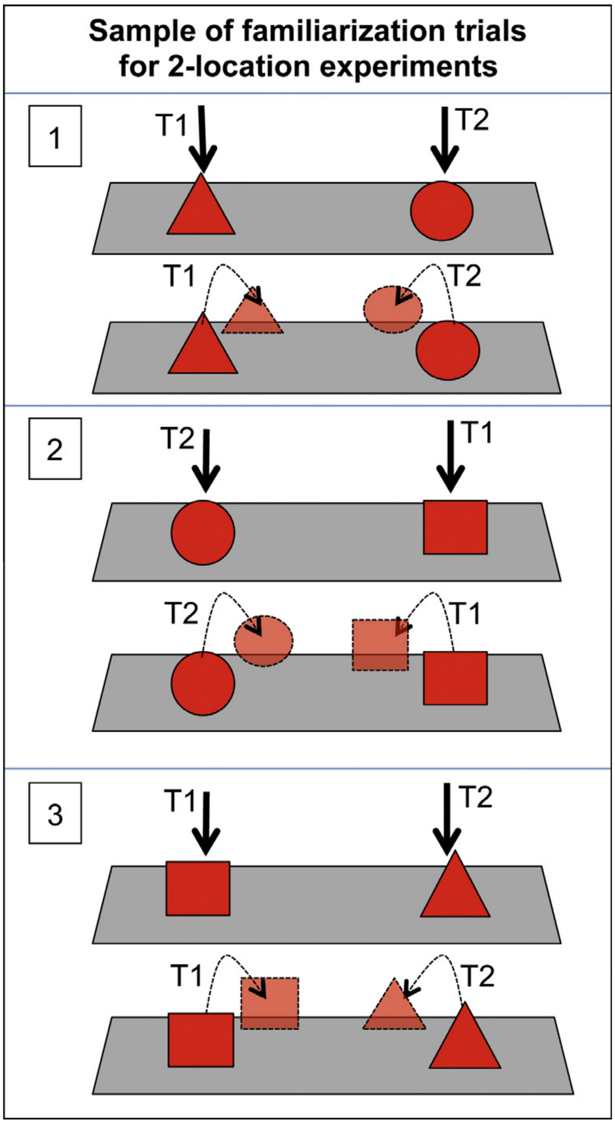

Fig. 5. Examples of three possible familiarization trials out of the six familiarization trials in experiment 2 (numbered 1, 2, and 3 in the figure).

was similar to that used at Rutgers University. The stage was made of black-painted wood and measured 125.7 × 50.8 × 43.2 cm.

3.1.4. Procedure

Infants were seated on a caregiver's lap facing the stage. The experiment began with the calibration procedure detailed in Section 2.1.4.

3.1.4.1. Familiarization. There were six familiarization trials. During each familiarization trial, two shapes out of the set of three were placed one at a time on the front of the stage. Infants viewed the shapes for 4 s, after which the experimenter moved the shapes to the back of the stage in the order they were initially presented. Infants viewed the shapes for an additional 6 s, after which the curtain was raised over the display (see Fig. 5, top panel). Trials were counterbalanced so that all three shapes appeared equally often in each location, were presented both first and last in presentation order, and were paired equally with the other shapes in the set.

3.1.4.2. Test trials: Two locations, difficult swap. Each of the three test trials began with two screens being placed toward the back of the empty stage. Two objects out of the set of three were then placed

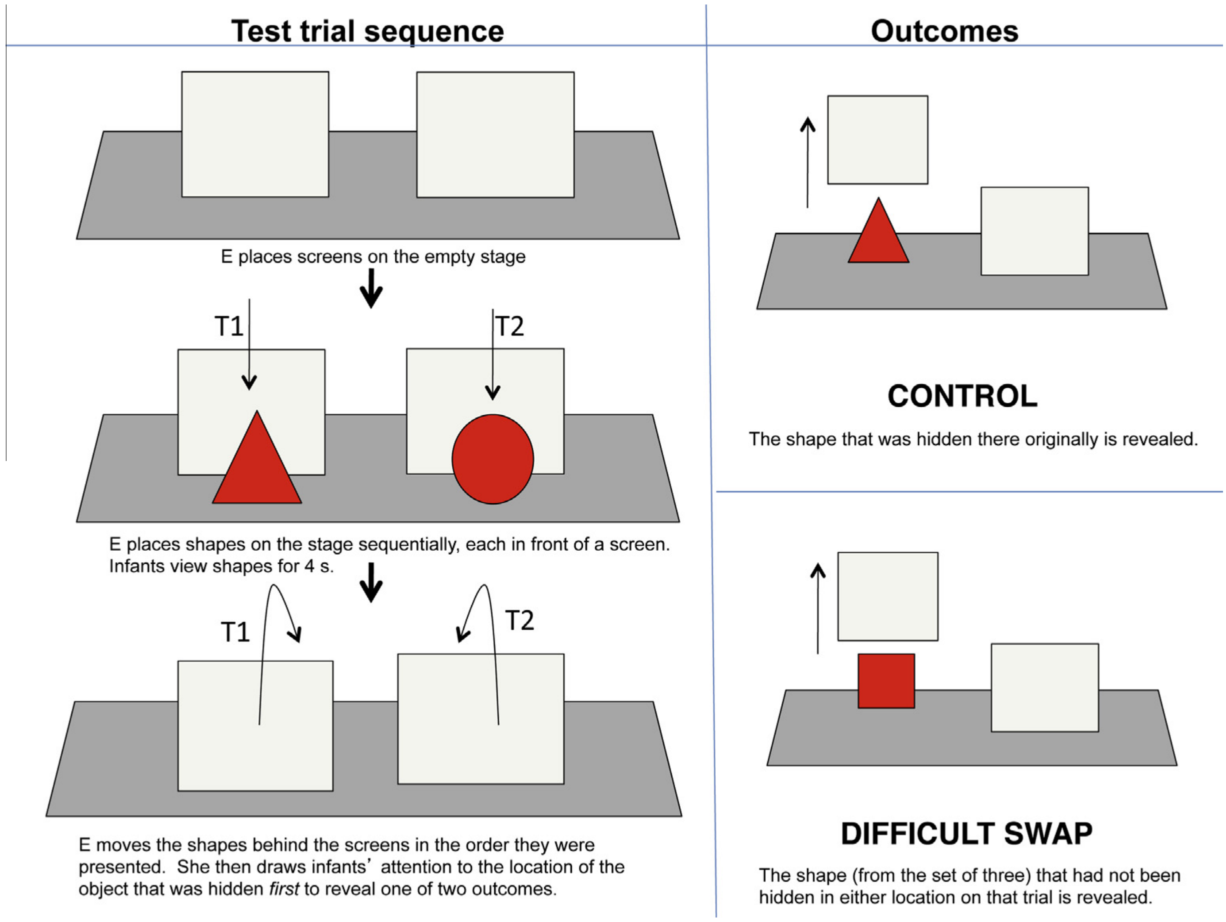

Fig. 6. Shows the first of three test trial sequences of experiment 2 with its two experimental outcomes (*control*, top right panel, and *difficult swap*, bottom right panel). Not shown are the second and third test trials in the sequence. In the second test trial, the square and the disk were placed on stage then hidden behind their respective screens. On this trial, in the *control* outcome, the screen covering the disk was removed to reveal the disk. In the *difficult swap* outcome the same screen was removed to reveal the triangle. In the third test trial, the triangle and square were placed on stage and hidden behind their respective screens. On this trial, in the *control* outcome, the screen covering the square was removed to reveal the square. In the *difficult swap* outcome the same screen was removed to reveal the disk. Thus, in the *difficult swap* condition, the probed object was swapped for the one shape from the set of three that was not present on that trial. Across these trials, each of the three shape pairs was tested in turn. During *control* outcome test trials, the probed object was the shape that was expected in that location. Across control trials, each of the three shapes was tested.

one at a time on the front of the stage in alternate positions to the previous trial. After 4 s the objects were hidden one at a time each behind their respective screens. The experimenter then drew the infants' attention to the location of the shape that was hidden *first* by jingling bells she wore around her wrist. She then raised that screen to reveal either the shape that had been hidden there originally (*control* outcome) or the shape from the set of three that had not appeared on that particular trial (*difficult swap* outcome) (Fig. 6).

An observer blind to outcome (*control* or *difficult swap*) measured looking time during the session. Two additional observers who were blind to outcome rescored the infants' looking time after the experiment (reliability was above 0.90).

3.2. Results

Analyses were based on 70 total test trials. Two additional trials from the original total of 72 were excluded due to experimenter error. A 3 (Trial) × 2 (Condition: control or difficult swap) repeated measures ANOVA showed no main effect of Trial ($F_{2,40} = 1$, $p = 0.37$, $\eta^2 = 0.048$) and no Trial × Condition interaction ($F_{2,40} < 1$, $p = 0.42$, $\eta^2 = 0.043$), but there was a significant effect of Condition ($F_{1,20} = 4.5$, $p = 0.047$, $\eta^2 = 0.184$); infants looked significantly longer at the *difficult swap* condition than at the *control* condition.

Fig. 7 shows the mean looking times for both conditions. Comparisons of group means using Student's t showed infants in the *difficult swap* condition looked significantly longer than infants in the *control* condition (t_{22} = 2.65, p = 0.015, two-tailed). Although there was no main effect of Trial, the largest effect occurred on the first trial (t_{22} = 2.418, p = 0.024, two-tailed), as is often the case in violation-of-expectation experiments.

3.2.1. Bayes Factor analysis

Bayes Factor analyses conducted on the data from experiment 2 revealed odds of 10.98:1 against the null hypothesis (see Fig. 8, solid lines, for plots of the cumulative probability distribution functions), far above the 3:1 level odds that are considered equivalent to a p value of 0.05 (Gallistel, 2009). This provides powerful evidence that infants do indeed recall the shape of the harder-to-recall object and are surprised when it changes.

Since Bayes Factor analysis gauges support for one hypothesis vs. another, it allows us to examine data across multiple experiments that test the same hypotheses. This is useful when one experiment replicates another experiment; the combined data provide further evidence that a given hypothesis is supported. In experiment 2, we replicated and extended the results of Káldy and Leslie (2003) by showing that 9-month-old infants did indeed notice a change to the shape of the harder-to-recall of two objects hidden in two locations even when we gave them only one means of succeeding at the task. A reanalysis of the Káldy and Leslie's original results using Bayes Factor yields odds of 16.3:1 against the null with a sample size of 24 9-month-olds. Taken together, these studies suggest robust recall of the specific shape of the object at the harder-to-recall location. Indeed, Bayes Factor analysis confirms this, yielding "crushing" odds of 312.5:1 against the null hypothesis when the looking time data from Káldy and Leslie (2003) were combined with the looking time data from experiment 2. Fig. 8 (dashed lines) shows the CDFs for the combined data (*control* and *swap* conditions).

3.3. Discussion

When 9-month-old infants only had to keep track of objects in two locations, they could detect a change in the shape of the harder-to-recall object. Experiment 2 controlled for the confound in Káldy and Leslie's (2003) original design, because the change was a "pure" identity change of the harder-to-recall object, no longer confounded with a possible location change of the easier-to-recall object. Thus, infants were given only one way to succeed at the task; they had to recall the shape of the object hidden in the probed location on a given trial, and notice that the shape had changed. They could not have

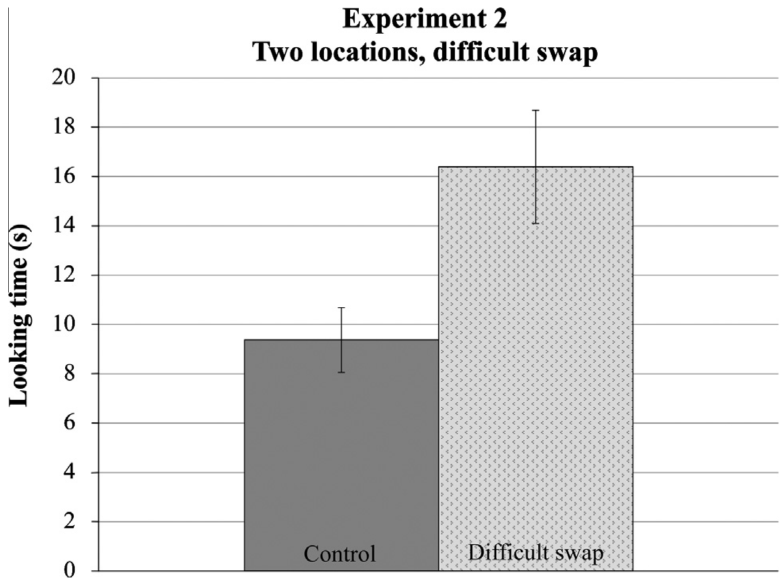

Fig. 7. Mean looking time for experiment 2. Error bars show ±1 SEM.

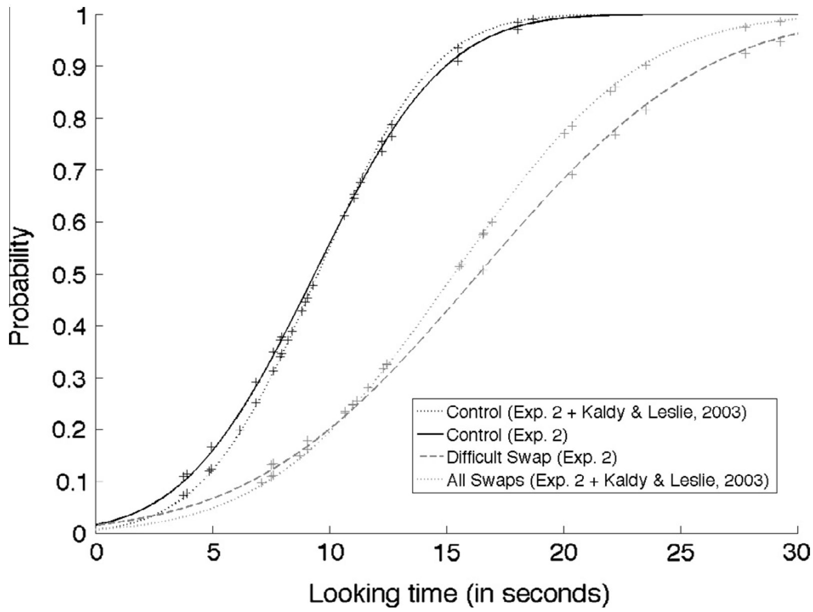

Fig. 8. Theoretical CDFs of looking time data (control = solid line, difficult swap = dashed line), along with the probability of the data itself (crosses) for 9-month-olds in experiment 2, as well as CDFs of the combined data of experiment 2 and the data from the control and swap conditions of Káldy and Leslie (2003) (dotted lines) along with the probability of the data itself (crosses). Experiment 2 tested infants with a *difficult swap*, while Káldy and Leslie (2003) tested infants with an *easy swap*. Thus, the combined data tests whether infants detect *any* type of change to the shape of the probed object.

succeeded simply by detecting a globally novel shape, since they were familiarized to each shape equally during familiarization trials, or by detecting the other shape that was present on that trial but was locally novel, since they were tested with the third object from the set.[3]

The results of experiment 2 therefore show that 9-month-old infants can indeed keep track of two shapes, and can do so robustly, when they are required to keep track of only two locations. This suggests that infants' failure in experiment 1 was driven not by the difficulty of the identity-recall task, but by the number of locations.

Nine-month-old infants failed in experiment 1 while they succeeded in experiment 2. In experiment 3, we go back to the three-location design of experiment 1. This time, however, we present this to infants in a way that should be easier for them if the source of the difficulty stems from processing three object identities. Infants' memory for the second-hidden object was once again probed, but the tested shape was swapped for the shape that was hidden *last*, that is to say, was the easier-to-recall shape. Infants could detect the change by noticing that the location of the easier-to-recall object had changed, or by noticing an identity change in the probed object itself. If, despite these attempts, infants *still* fail, it will underscore that the source of their difficulty is the number of locations in which they had to track objects rather than the difficulty of the identity-recall task.

[3] Some evidence from adult work (e.g., Saiki, 2003) suggests that it is harder to detect an identity change when objects in an array swap features vs. when an object changes to a novel identity not present on that trial. However, in the adult studies, the entire array was visible throughout and change could occur to any object in the array. This meant that all objects were within the same focus of attention, increasing the likelihood of correspondence errors and therefore making a detection of a feature swap more difficult (e.g., Cohen & Ivry, 1989; Prinzmetal, 1981; Treisman & Schmidt, 1982). Infants in our study encountered all shapes from the set of three during familiarization trials (so that none were globally novel), and were then tested on the harder-to-recall object *by itself* (reducing the likelihood of correspondence errors. Thus, in order to detect the change, infants in our task had to recall the featural identity of the probed object, expect *that specific shape* to appear in the probed location, and notice that that it had failed to appear. Further, although 9-month-old infants can recall more than one featural identity when tracking objects in two locations, we predict hat 9-month-old infants will fail to detect any change to the probed object when tracking three objects in three locations, even when the probed object is swapped with an object which is familiar to the infants but which did not appear on that trial, because infants will have no expectations about the identity of the probed object. This is a question for future research.

4. Experiment 3: Three locations, easy swap

4.1. Method

4.1.1. Participants

Participants were 12 healthy full-term infants (5 females) between 34.9 and 44.4 weeks of age (mean = 39.7 weeks, *SD* = 2.5 weeks). Eleven infants were tested at Rutgers University, and one was tested at Johns Hopkins University. An additional four infants were excluded due to fussiness (2), experimenter error (1), or parental interference (1).

4.1.2. Design, apparatus, and procedure

The design, apparatus, and procedure of experiment 3 were identical to those in experiment 1, except that the test outcome was different: when the experimenter removed the screen that occluded the second-hidden object, she revealed the object that had been hidden *last* (*easy swap* condition; Fig. 2).

4.2. Results

Since everything about the procedure leading up to the revealed outcome was identical to experiment 1, infants' looking times in experiment 3 were compared to the looking times of the control group in experiment 1 (for ease of comparison, data from both conditions of experiment 1 are plotted with the data from experiment 3 in Fig. 9).

Analyses were based on 96 total test trials. Results of a Trial (4) × Condition (2) repeated measures ANOVA showed no effect of Trial ($F_{3,66} = 1.48$, $p = 0.22$, $\eta^2 = 0.063$) and no Trial × Condition interaction ($F_{3,66} < 1$, $p = 0.7$, $\eta^2 = 0.022$). There was also no main effect of Condition ($F_{1,22} < 1$, $p = 0.86$, $\eta^2 = 0.001$), suggesting infants did not look longer at the *easy swap* outcome than the *control* outcome.

4.2.1. Bayes Factor analysis

Support for the null hypothesis comes from Bayes Factor analysis, with odds of 4.14:1 in favor of the null (see Fig. 10 for plots of the theoretical cumulative probability distribution functions of the data). We also collapsed across both the *difficult swap* and *easy swap* conditions and compared them to the *control* outcome. In this case, we were interested in whether infants can detect *any* change, not just a particular type of change. Bayes Factor analysis again yielded odds in favor of the null, 4.6:1.

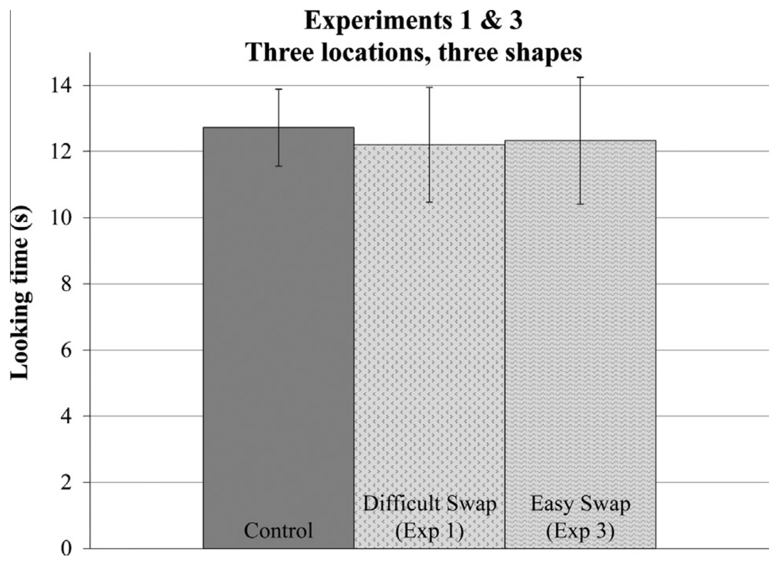

Fig. 9. Mean looking times from experiments 1 and 3. Error bars represent ±1 SEM.

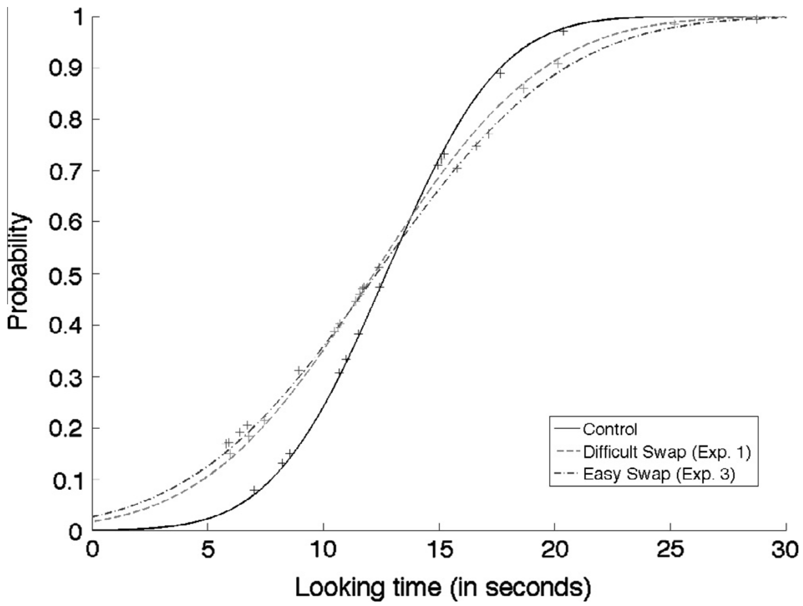

Fig. 10. Theoretical CDFs of looking times (lines), along with the probability of the data itself (crosses) in *control* and *easy swap* conditions for 9-month-olds in experiment 3. For ease of comparison, the *difficult swap* condition from experiment 1 is re-plotted.

Taken together, these data suggest that infants can recall the shape of the harder-to-recall object when tracking objects in two locations, but not when tracking objects in three locations.

4.3. Discussion

Infants in experiment 3 failed to detect that the harder-to-recall object had changed shape, even though we made the task easier by giving infants two means to detect a violation: to succeed, infants could have detected either a location change of the easier-to-recall shape or a shape change to the probed object. Experiments 1 through 3 show that infants are failing to recall the specific shape of the probed object because a third hiding location was present in the display. Thus, 9-month-olds can indeed recall two object identities, but only when they have no more than two locations to keep track of. When infants are required to track objects in three locations, their ability to recall which object went where is limited.

Further, since infants were given two means to detect a violation in experiment 3, but failed to use either means, this gives us some clues about infants' representations of the objects in the display when three objects were hidden in three locations. One possibility is that infants failed to recall the featural identity of *any* object in the display, including the last-hidden, easier-to-recall object (also a possibility for infants in experiment 1). Under this possibility, tracking identities across three separate locations is so difficult for infants that they are left with only inklings of the objects in each location and no identifying featural information about any object. By contrast, Káldy and Leslie (2003) found that infants of this age do remember the shape of the last-hidden, easier-to-recall object when tracking two objects in two separate locations. Another possibility, then, is that infants successfully recalled this identity, but were agnostic about the identity of the probed object. Under this possibility, infants would have had no expectations about the shape in the probed location, nor even that the shape in the probed location should be *distinct* from the last object they saw hidden. This possibility seems likely, given previous work showing that even 6.5-month-old infants can recall the shape of the last-hidden of two objects, but not the first-hidden (Kibbe & Leslie, 2011; Káldy & Leslie, 2005). Future work will disambiguate these two possibilities.

Is the three-location task simply too difficult for infants, or might infants develop the capacity to keep track of shapes when tracking objects in three locations? Experiment 4 asks whether

12-month-old infants can detect the difficult swap in the three-location task. If 12-month-olds succeed, it would suggest that the cognitive resources required for the task undergo rapid development between 9 and 12 months of age.

5. Experiment 4: Three locations, difficult swap (12-month-olds)

5.1. Method

5.1.1. Participants

Participants were 24 healthy full-term infants (14 females) between 47.1 and 55.6 weeks of age (mean = 51.8 weeks, SD = 3.2 weeks). Twenty-three infants were tested at Rutgers University, and 1 was tested at Johns Hopkins University. An additional 7 infants were excluded due to fussiness (3), experimenter error (2), or parental interference (2). Infants were divided into two groups ($n = 12$ per group), where each group saw one of two possible outcomes.

5.1.2. Design, apparatus, and procedure

The design, apparatus, and procedure of experiment 4 were identical to those in experiment 1 (Figs. 1 and 2).

5.2. Results

Analyses were based on 96 total test trials. Looking times were analyzed in a Condition (2) × Trial (4) repeated measures ANOVA. There was no effect of Trial ($F_{3,66} = 2.03$, $p = 0.12$, $\eta^2 = 0.084$) and no Trial × Condition interaction ($F_{3,66} = 2.33$, $p = 0.08$, $\eta^2 = 0.096$), but there was a significant main effect of Condition ($F_{1,22} = 5.12$, $p = 0.03$, $\eta^2 = 0.189$). Unlike the 9-month-olds in experiment 1, the 12-month-olds in experiment 4 looked significantly longer at the *difficult swap* outcome than the *control* outcome ($t_{22} = 2.26$, $p = 0.03$, two-tailed). Mean looking times are plotted in Fig. 11.

Bayes Factor analysis shows support for the alternative hypothesis, with odds of 4.6:1 against the null hypothesis (Fig. 12).

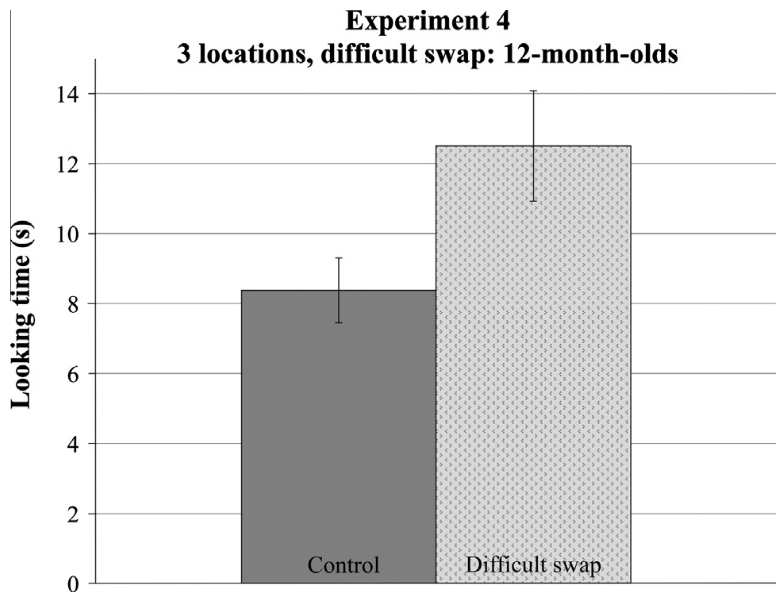

Fig. 11. Mean looking times for 12-month-olds in experiment 4. Error bars represent ±1 SEM.

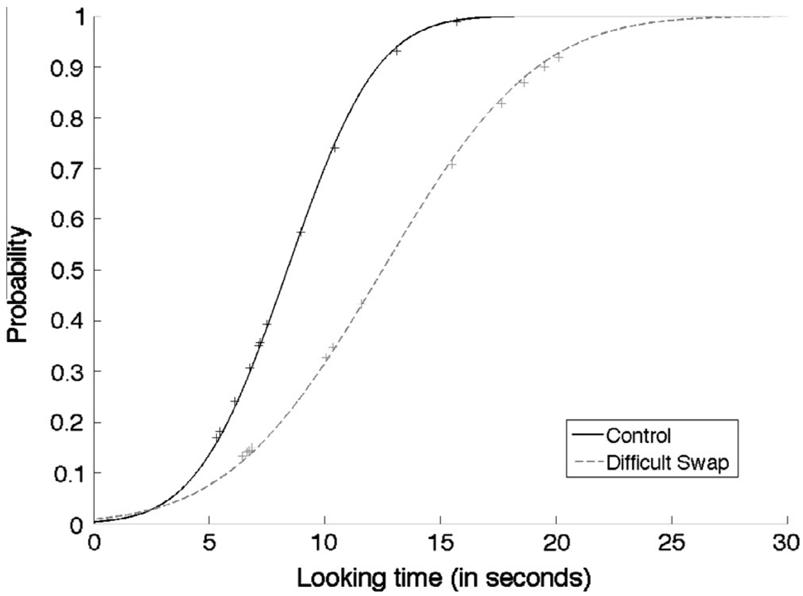

Fig. 12. Theoretical CDFs of looking times (lines), along with the probability of the data itself (crosses) in the *control* and *difficult swap* conditions for 12-month-olds in experiment 4.

5.3. Discussion

Twelve-month-olds succeed in the three-location, difficult swap task; the limits on 9-month-olds in this task ease within a few months.

6. General discussion

We began by positing a featureless object representation that essentially indexes the object's location. The contrasting classical view is that object representations begin, both developmentally and in on-line processing, as bundles of features. By contrast, we argue that they begin as object indexes to which features may then be bound. Here, we showed that it is the number of locations in which infants have to track hidden objects, rather than number of shape-featural object identities, that limits infants' WM for 'what'.

In the current series of studies, we hid objects sequentially, each shape in its own location. We then revealed that one of the objects had apparently changed shape. We manipulated the number of objects in locations infants had to track. We also manipulated the type of shape change infants saw. In the case of three locations, we swapped the object of interest for the last-hidden object (*easy swap*) or for the first-hidden object (*difficult swap*). In the case of two locations, we swapped an object to which infants had previously been familiarized but which had not been used on that swap trial (*difficult swap*). We made the distinction between a "difficult" and an "easy" swap based on the number of ways infants could possibly succeed at the task. In an "easy" swap, the object that is hidden *last* is swapped for the probed object. Thus, to notice the swap, infants could recall either the location of the last-hidden object or the identity of the probed object. In a "difficult" swap, infants can no longer use their memory of the location of the last-hidden, easier-to-recall shape in order to detect a change to the probed object. This is why experiments 1, 2, and 4 are "difficult swaps" while experiment 3 is an "easy swap". Regardless of the number of objects/locations or the type of swap, we always tested infants' recall for the object that was hidden second-to-last, and so was harder to recall than the object they saw hidden last.

Two patterns emerged. First, as the number of locations in which infants had to track objects increased, their ability to keep track of *what* shape went *where* decreased. In experiment 1, 9-month-olds were unable to recall the shape of the second-hidden of three objects when the stimuli consisted of three locations and three shapes. In experiment 2, 9-month-olds succeeded at recalling the shape of the second of three objects when only two locations were present. This finding showed that 9-month-old infants really do recall the specific shape of that second object, and do not simply rely on their memory of the easier-to-recall object, a possibility not ruled out by Káldy and Leslie (2003). Experiment 3 showed that 9-month-old infants failed in the face of three hiding locations even when we made the identity-recall task easier by giving infants multiple means of detecting the change. Experiments 1 through 3 showed that when 9-month-old infants viewed hiding events across two locations, they were able to recall which shape went where, but when the number of objects/locations increased to three, they failed. In both the two-location task and the three-location task, infants were always tested on the second-to-last hidden object; the only difference between the two tasks was the presence of a third location and third object.

The second pattern that emerged was that infants' ability to keep track of what went where increased with development. At 9 months, infants could keep track of which of two shapes went in which of two locations, but their performance broke down in the face of three locations. By 12 months, infants were able to successfully keep track of the specific identities of (at least) two shapes across three locations.

The literature on WM for 'how many' strongly suggests that there is no change in the limit of about 3 across the first year of life. By contrast, the limit on 'what' appears to increase over the same period. Our results show that these limits are not completely independent; rather, as infants have to track more individuals, WM for identities suffers. What accounts for this contrast?

6.1. *The resolution-limited hypothesis*

One possibility is that infants start out with severe limitations on the resolution of WM; these limitations then relax as infants approach the second year of life (and perhaps beyond). Zhang and Luck (2008) proposed that adult WM is limited to a fixed number of high-resolution slots with which to store the contents of a visual array (we refer to this model as the fixed-resolution slot model). Infants also appear to have a fixed number of slots, close to the adult limit of about 4 (Feigenson & Carey, 2003, 2005; Feigenson et al., 2002). However, our current results, and our previous results with 6-month-old infants (Kibbe & Leslie, 2011) show that, contrary to Zhang and Luck's adult model, not all of these slots are created equal. Even when infants' set size limit is not exceeded, infants can only recall a subset of objects in detail, while retaining an inkling of the objects for which identifying information has been lost. If there is indeed a resolution limit on WM, the infant evidence suggests that some slots have a higher resolution than others.

Although Zhang and Luck (2008) concluded that the fixed-resolution slot model provides the best fit for their data, they also suggested an alternative model, which may better account for infants' pattern of performance. The alternative model also posits a fixed number of slots, but the precision of each representation is dictated by a limited resource that must be shared across the slots (we refer to this model as the resolution-limited model). Zhang and Luck use a metaphor in which the WM resource is represented by a bottle of juice and each slot is represented by a cup. It is possible to pour equal amounts of the juice into each cup, so the resource is shared equally across slots. Or, it is possible to fill up one of the cups, and only put a small amount of juice in each of the other cups, resulting in a high-resolution representation in one slot, and lower-resolution representations in the other slot. An additional possibility is that there is not a fixed number of slots; rather, WM can be thought of as a flexible resource that can be allocated strategically, such that a small number of items can be represented with high resolution, or a larger number of items can be represented with lower resolution (Bays & Hussain, 2009; Huang, 2010).

The resolution-limited model has been used to explain infant data that suggest a tradeoff between the number of objects that can be held in WM and the detail with which each object is represented. Zosh and Feigenson (2012) used a manual search method to assess the precision with which 18-month-olds' represented objects. One, 2, or 3 different objects were placed on top of a box, and then hidden inside the box through an opening at the front. Infants were allowed to retrieve the correct number of objects, but sometimes the objects switched identities. Infants continued to search for missing items when only one or two objects were hidden, indicating they recognized that the objects they removed were not the same as the objects that were hidden. However, when three objects were hidden, infants only noticed a switch in object identity when the difference in the items was sufficiently salient, as in when an object turned into a blobby non-object. Zosh and Feigenson (2012) concluded that the pattern of results they observed is consistent with a capacity/resolution tradeoff: as the number of objects increased, infants' representation of each object became coarser.

Zosh and Feigenson (2012) showed infants multiple objects being hidden at once in a single location, a task which makes different attentional demands than our multiple-location studies. In our studies (experiments 1–4; Kibbe & Leslie, 2011; Káldy & Leslie, 2003, 2005), infants have no way of knowing which location they will be asked to recall. As infants watch the sequence of events unfold, they might adjust the way they allocate WM resources as each new item is hidden, with more resources allocated to each subsequent object in the hiding event. Under the resolution-limited hypothesis, we might predict that the last-hidden object would be represented with the highest resolution. Infants' performance across multiple-location VOE tasks does provide some support for this hypothesis. At 6 months, infants can recall the shape of the last-hidden object (Káldy & Leslie, 2005), but cannot recall the shape of the first-hidden object, although they are surprised when it disappears completely (Kibbe & Leslie, 2011). Under the resolution-limited hypothesis, 6-month-olds' pattern of performance would be due to allocating more resources to the most recently hidden object, and fewer resources to the first-hidden object, such that they have a high-resolution representation of one object, and a low-resolution representation of the other. Infants were unable to detect when the first-hidden object changed shape because their memory representation of the shape at that location was fuzzy. And although this fuzzy representation does not contain enough information to identify the shape, infants would nevertheless remember that some object was hidden in that location.

By 9 months of age, infants have more resources at their disposal (more "juice in the bottle") to allocate to encoding objects in the array; 9-month-olds can recall two out of two shapes where 6-month-olds can recall only one shape out of two. But when there are three objects in the to-be-remembered array, 9-month-olds perform more like 6-month-olds. If 9-month-olds have a fixed amount of resources to share across objects, their highest-resolution representation may be the most recently viewed object, while the rest of the array is subject to lower-resolution encoding. When there are only two shapes in the array, resolution of the harder-to-remember object is good enough to detect a change in shape; but with three shapes in the array, the fidelity with which each object is represented is no longer sufficient. By 12 months, infants are able to represent at least two of the objects in a 3-location sequence with enough fidelity to detect a shape change.

6.2. The binding-limited hypothesis

The resolution-limited hypothesis has limitations in its explanatory power. Resolution-limited models were constructed based on adult change-detection studies in which the entire contents of the visual array disappear instantaneously and simultaneously (thus in a way that specifies they no longer exist), and representations are retained over only brief intervals before they are compared to a new array in which one or more of the items might have changed (see Section 1.2.1). Since the objects disappear simultaneously, decisions about where to allocate limited resources can be made all at once. Thus, many adult studies seem to show an overall decrease in resolution as set size increases or, alternatively, as objects get more complex (e.g., Alvarez & Cavanagh, 2004). Furthermore, these studies may not be targeting the mid-level object-indexing mechanisms at all, that is, the mechanisms that track objects in 3-D space over extended periods as they move in and out of occlusion because perceptual information specifies their continued existence (Michotte, 1963; see also Flombaum & Scholl, 2006).

By contrast, for infants in our experiments (and, indeed, for both infants and adults in most real-world situations), decisions about resource allocation had to be made dynamically as sequential events proceeded in a 3-D space containing persisting objects. At the start of a test trial, infants had no way of knowing that the objects would eventually be hidden from view, nor which location would be probed. Once the first object was hidden from view, it is likely that infants would dedicate all or most of their limited WM resources to encoding that object, equivalent to filling up the metaphorical cup with all the juice from the bottle. Once the second object is hidden, what happens to the representation of the first-hidden object? Do resources get re-allocated, such that each representation ends up with some share of the resources? What controls the decision to withdraw resources from the first-hidden object and dedicate them to the last-hidden object? Are resources stolen from items already in WM, so that the items suffer a *decrease* in resolution as new items are encoded?

A different possibility is that infants are limited in the number of bindings between features and object indexes that can be maintained in WM. When infants view the sequence of events in a multiple-location violation-of-expectation task, they have to keep track of what shape went where in order to respond correctly when their memory for each location is probed. This requires not only successful binding of features to object indexes but also the maintenance of those bindings.

If infants are limited in the number of feature bindings they can maintain, we would expect them to be able to recall the shape of only a subset (or, even none) of objects, but still be able to recall that an individual was hidden in each location (Leslie et al., 1998). Under this hypothesis, keeping track of objects in multiple locations can be done relatively cheaply and in parallel (Pylyshyn & Storm, 1988; Sagi & Julesz, 1985; Scholl & Pylyshyn, 1999). However, binding identifying features to those objects and maintaining those bindings over time must be done serially (Sagi & Julesz, 1985). In adults, both binding and maintenance require attentional resources (Cohen & Ivry, 1989; Prinzmetal, Presti, & Posner, 1986; Wheeler & Treisman, 2002). Therefore, infants, whose ability to allocate attention endogenously develops across the first year (Colombo, 2001), will show an increase in the number of identities they can recall over this period while the number of individuals they can track should stay about the same.

The binding-limited hypothesis suggests that limited attentional resources must be allocated to maintaining the contents of locations during multiple-location hiding events such as the ones infants saw in our experiments. Since infants have no way of knowing which objects will be hidden and which locations will be probed, they must attend to each hiding event in turn and update their representation of the scene as best they can. And since objects are hidden sequentially, each subsequent hiding event can be thought of as a distractor event, drawing infants' attention toward the object that is currently being hidden. The last object to be hidden would be the most recent focus of attention, and, therefore, would be the most likely to have identifying information persistently bound to it. On this model, it is the re-allocation of attention that leaves the first-hidden object with insufficient resources to maintain the binding. The effect is to leave a bare index to the object's location, but no way for the infant to remember what the object looked like. We have called these bare object representations "inklings" (Kibbe & Leslie, 2011; see also Baillargeon, Li, Ng, & Yuan, 2009, for a review of other findings that suggest infants can represent an object's existence without its identifying features).

When 9-month-olds can track and recall shapes in two locations, but have trouble with three locations, it suggests that the bindings between feature and object are fragile and maintenance of those bindings is contingent upon the attentional demands of the task. By 12-months, infants can recall at least two shapes when tracking three objects in three locations, suggesting that the maintenance of these bindings becomes easier as infants develop (cf., Ross-Sheehy, Oakes, & Luck, 2011).

The binding-limited model can also explain results on infants' ability to track 'how *much*' in foraging tasks. When infants watch different numbers of crackers being hidden in two locations, they reliably choose to forage in the location containing more crackers, apparently based on the total surface area or volume of the set (Fiegenson, Carey, & Hauser, 2002). To do this, infants need to bind size features to the objects and to accumulate a total size for each set. However, infants only succeeded if all the crackers were hidden in each location in succession, but not if the crackers were hidden in alternation (Feigenson & Yamaguchi, 2009). Our model explains that switching between alternating hiding events reduces infants' ability to maintain size-feature bindings for indexes already in memory. Successive hiding presumably allows the extraction of the total accumulated size for one set before attention is drawn away from it by the hidings taking place later at the second location. The attentional constraints on the maintenance of feature bindings can also explain the results of Zosh and Feigenson (2012); even though infants could not recall the specific identities of three objects, they nevertheless expected there to be cohesive, bounded *objects* in the box, and were surprised when a non-object blob emerged from the box.

6.3. Binding limitations affect physical reasoning

Across the four experiments in this paper, we showed that increasing the number of hiding locations limited infants' ability to keep track of the identities of the objects hidden in those locations. Our results are consistent with the physical reasoning (PR) framework developed by Baillargeon and colleagues (Baillargeon et al., 2012; Wang & Baillargeon, 2008). They propose that when infants are faced with a physical event, such as an object going behind a screen, they first categorize the type of event (in this example, occlusion) and locate the objects that are involved in the event (an occluder and an occludee, for example). At this stage, infants' representation of the object that will become occluded is relatively sparse: for example, infants may represent that the object is cohesive, bounded, and non-agentive, but may not represent its color or shape. This stage of representation is akin to our "featureless object representation"; infants represent "objectness" without necessarily identifying *what* the object is. Under Baillargeon and colleagues' PR framework, the kind of featural 'what' information that infants will represent depends on how they have categorized the event and which features they have yet identified as relevant for reasoning about how objects behave in these events (e.g., Baillargeon, 1991; Hespos & Baillargeon, 2001; Wilcox, 1999). Featural information, such as shape, must then be bound to the earlier structural object representation, which represents the location and mechanical properties of the object.

Our results suggest that, as infants attend to each new occlusion event in turn, it becomes difficult to maintain the bindings between featural information and object indexes. Thus, the limit on infants' WM for 'what' restricts their ability to reason about the outcomes of physical events. By 9 months of age, infants have identified 'shape' as a feature that is relevant to occlusion events, successfully individuating objects by shape alone by 4.5 months of age (Wilcox, 1999). But when 9-month-olds had to keep track of objects across three occlusion events, they were unable to form expectations about the shape identity of the object hidden in the probed location, because the increased attentional demands resulted in the loss of the relevant featural information. However, even when featural information is lost, infants still have expectations about the structural/mechanical properties of the object: they expect an object (Kibbe & Leslie, 2011) and not a non-object (Zosh & Feigenson, 2012). Since occlusion has been shown by Baillargeon and colleagues to be the earliest-understood of the hiding-event types (see Baillargeon et al., 2012), we predict that our results will generalize to the later-understood event-types, such as containment and covering (as long as the features tested have been identified as relevant for these event categories).

We assume that object indexing and object WM can interface between perceptual objects (which encompass both 2-D and 3-D arrays) and objects in physical-reasoning systems such as those envisaged by Wang and Baillargeon (2008) and Baillargeon et al. (2012). Such physical-reasoning systems are upstream from object indexing and object WM and inherit their limitations. It would not be surprising to find top-down attentional effects on these downstream systems. For example, 9-month-old infants failed to recall the color of objects hidden in a two-screen violation-of-expectation task (Káldy & Leslie, 2003), consistent with work showing that infants do not identify color as a relevant occlusion variable until 11.5 months of age (Wilcox, 1999). However, we hypothesize that the only top-down effects would be of this sort.

6.4. Conclusion

We provided evidence that the distinct limits for 'what' and 'how many' in infant WM are in keeping with the object-index structure put forth by Leslie et al. (1998). Individuated objects are tracked relatively cheaply while maintenance of identifying information about each object is costlier. The more locations infants have to track, the fewer identities they can recall. These results, together with previous results with 6-month-olds (Kibbe & Leslie, 2011), suggest that infants' WM supports a featureless object representation, which can have featural information bound to it, but only at some cost.

We further showed that, as infants develop, their ability to maintain feature bindings across multiple locations improves. However, we do not suggest that infants start out with featureless object representations and subsequently construct feature bundles that replace the more primitive featureless representations. Rather, the featureless object representation is possible and useful at any stage in development, including, we would argue, adulthood.

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