DEVELOPMENT OF EFFICIENT ENCODING IN VISUAL WORKING MEMORY

by

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ABSTRACT OF THE THESIS

Development Of Efficient Encoding In Visual Working Memory

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Previous research has shown that infants' visual working memory (WM) capacity for objects appears to increase over the first year of life, from one object at 6 months to three objects at 12 months (Ross-Sheehy, Oakes, & Luck, 2003; Leslie & Kaldy, 2007). However, other evidence suggests that infants are able to keep track of multiple objects, without necessarily any identifying information, and that this object-tracking capacity does not seem to change over the first year of life (Feigenson, Carey, & Hauser, 2002; Feigenson & Carey, 2003). This apparent contradiction in findings prompted us to attempt to tease apart WM for individuated objects and for object identities (features) in infants. Our research indicates that infants, like adults, have a fixed number of slots in which to store objects, but the amount of resources available for encoding identifying featural information increases over the first year of life, resulting in an increase in the resolution of WM representations.

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I would like to thank Alan Leslie, Katya Saunders, and all the members of the Cognitive Development Lab for their support and assistance in completing the research presented in this thesis.

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Introduction

As an infant looks, crawls, and later walks around the world, she encounters a very complicated environment filled with people and objects that are always coming and going. In order to learn about the world, she must be able to keep track of the things that she has seen, remember what and where they are, and understand how those things interact with the world. For example, what might the infant think when she sees her favorite red ball roll under the couch, and a blue ball roll out the other side? In order to understand what has happened, she must remember that her ball continues to exist once it is under the couch. She must also remember that her ball is red and not blue. Further, she must understand that it is impossible for her ball to magically change color, thereby ruling out the possibility that the ball that rolled out of the other side of the couch is not her favorite red ball.

In this simple example, the infant is faced with a lot of information that she must integrate and process in order to represent the situation veridically. She must use the spatiotemporal properties of the ball in order to keep track of it. She must use the features of the ball (e.g. round, red, small) to identify it. Once the ball is hidden from her view, she must be able to hold this information in her memory to correctly represent *where* the ball is and *what* it is. Once she sees the blue ball, she must then be able to compare what she sees with what she remembers. That is, she must *individuate* the ball, forming an object representation, and then *identify* the ball, using the information she has stored about the ball in order to compare it to the ball she is currently seeing (Tremoulet, Leslie,

& Hall, 2000). If she is able to do all this, she will rightly represent the blue ball as a completely new object, distinct from her favorite red ball.

What is the nature of infants' capacity to integrate all of the information with which they are presented and represent the world accurately? What information can they access and use to individuate objects and hold them in memory? In the above scenario, the infant must tell the balls apart using only featural information since the balls have the same spatiotemporal trajectories. Xu and Carey (1996) conducted a series of experiments in which they tested whether infants were able to do just that. In their experiment, infants saw a duck and a truck alternately disappearing and reappearing behind a screen, never visible at the same time. They then removed the screen to reveal either just a truck or both the duck and the truck. They found that 12-month-olds, but not 10-month-olds, expected two objects to be behind the screen, suggesting they could individuate the objects by feature. However, in another condition where infants were able to see both objects simultaneously before they were alternately hidden and revealed, both 10- and 12-month-olds were able to individuate the objects. Xu and Carey interpreted these results as indicating that, prior to 12 months of age, infants are only able to represent a general sortal "object". They argue that, between 10 and 12 months, infants develop more specific sortals: only when infants know *conceptually* what an object is are they able to use property information to individuate different objects, thus relying on long-term memory representations (see also Xu, Carey, & Welch, 1999).

Xu and Carey (1996) used highly complex stimuli in their experiments, showing infants toys with many different features and conjunctions of features. While the objects to be used were indeed categorically different, it is unclear whether they were sufficiently perceptually different for infants to discriminate them by feature when they were not able to visually compare them. Xu, Carey, and Quint (2004) used perceptually simpler objects in a similar task with 12-month-olds, and again found an effect of category only; however, they note that the shape differences between objects of different categories may more be salient to infants that the shape differences in the other stimuli they used. If infants are relying on long-term memory representations to individuate the objects, categorical differences should be sufficient. However, if infants are relying on a short-term memory representation, perceptually complex objects may be difficult to discriminate in memory and therefore difficult to individuate. In this case, infants would have to use the more reliable spatiotemporal information to individuate the objects. Since the path of the objects forms a continuous trajectory, infants are relying solely on this information would fail to represent two objects.

Indeed, when featural information is unreliable, adults will use spatiotemporal trajectories when forming object representations. Feldman and Tremoulet (2006) varied featural similarity of two objects traveling on opposing trajectories such that both objects begin in one of the two top corners of the screen, travel toward each other toward the center of the screen where they both disappear behind an occluder, bounce off each other, and end up in the bottom corners of the screen. However, because there is an occluder in the center of the screen, the trajectory is ambiguous: the objects can either be interpreted as bouncing off of each other or passing by each other. Feldman and Tremoulet found that when objects were more similar, subject saw the object trajectories as a straight motion path. As objects decreased in featural similarity, the bouncing percept dominated. For adults, when featural information is not sufficient for individuation, spatiotemporal information is relied upon. Interestingly, in the above experiment, these two sources of information do not give rise to the same percept (see also Scholl & Nakayama, 2004).

Infants, too, have access to multiple cues that they can use to individuate objects. They can use spatiotemporal information when featural cues are unavailable, unreliable, or not recallable (Bremner, et al., 2005; 2008). In order to use featural information to individuate objects that are not viewed simultaneously, features must be remembered when the objects are occluded. Infants in Xu and Carey's experiment were faced with featurally complex objects, and so it is possible that the younger infants did not have sufficient memory capacity to use featural cues to individuate the objects, relying instead on the spatiotemporal cues.

Thus, in order to gain robust understanding of infants' ability to form object representations, it becomes important to determine infants' capacity to remember different sources of information under conditions where the information content of the objects is controlled. That is, we must measure infants' visual working memory (WM) capacity for objects under different levels of information load.

Let us first look at cases where there are no featural differences between the objects that infants must remember, so infants must use spatiotemporal information to individuate them. These types of experiments, designed to assess how many objects infants could remember, can give us a raw estimate of infants' WM capacity. Feigenson and Carey (2003) used a manual search paradigm to test whether infants could keep track of multiple objects as they were hidden and retrieved from a single location. Twelve-month-old infants watched as 1, 2, 3, or 4 balls were placed one at a time inside a box. Infants were then prompted to remove some or all of the balls, leaving the box empty or leaving some balls remaining. Once some or all of the balls are removed, infants were given the box and allowed to search inside it (while the experimenter secretly held back any remaining balls. If infants search longer when there are balls remaining in the box as opposed to when the box is empty, they are able to keep track of the number of balls that went in, the number that came out, and therefore how many are left. Feigenson and Carey found that 12-month-old infants were able to keep track of up to three identical objects hidden one at a time in a box, but not four. In a similar study, Feigenson, Carey, and Hauser (2002) used a foraging task to assess how many objects 10- and 12-month-old infants could keep track of. They found that infants preferentially crawl to a container holding three crackers over a container holding two crackers, but showed no preference when asked to choose between three and four even three and six, suggesting a WM limit of 3. Indeed, infants as young as five months are able to discriminate between sets of two and sets of three objects in a habituation paradigm (Starkey & Cooper, 1980; Wynn, 1992; this ability is not just limited to objects but can be seen when infants are presented with collective entities moving together as a unit, as in Wynn, Bloom, & Chiang, 2002).

Summing together the results from many different experiments using many different age groups and many different methodologies, it appears that infants' WM capacity for objects, regardless of featural information, seems to about three across the first year of life.

What happens to infants' WM capacity when they not only have to simply keep track of *where* objects are but also *what* they are? Recall that Xu and Carey (1996) concluded from their results that, prior to the age of 12 months, infants are unable to individuate objects by feature. But Xu and Carey did not consider that their results could reflect a limited capacity for encoding the features of an object in WM. In experiments with much simpler objects than those used by Xu and Carey, infants younger than 12 months *are* able to individuate objects by feature. Kaldy and Leslie (2003) used a violation-of-expectation method to measure infants' WM for object defined by simple features (e.g. shape). Infants saw two objects hidden one at a time behind two screens, at which point one of the screens is raised to reveal either the object that was originally hidden there (control condition) or the object that had been in the other location (swapped objects condition). This method allows infants' memory for each object to be probed separately. They concluded that 9-month-old infants could remember the shapes of up to two objects by testing their memory for the object that was hidden first (that is, the harder to remember of the two items) (see figure 1). However, in a similar study with six-month-olds, Kaldy and Leslie (2005) found that infants in this age group can only remember the shape of one object, indicating a WM capacity of one object identity. Using a different methodology, Ross-Sheehy, Oakes, and Luck (2003; see also Oakes, Ross-Sheehy, &

Luck, 2006) tested WM capacity of infants in three age groups, 6.5-month-olds, 11-month-olds, and 13-month-olds. Infants were shown two computer monitors; on one monitor was a display in which 1, 2, or 3 colored squares were shown briefly, disappear, and then are shown again, over and over. On the other monitor, one or more of the colors changes at each presentation. If infants remember the colors of the objects over the interval when they are not present, they will prefer to spend more of their time looking at the changing stream. Ross-Sheehy, Oakes, and Luck found an increase in WM capacity for objects defined by one feature, from one at 6.5 months old, to two at 11 months old, to three at 12 months old.

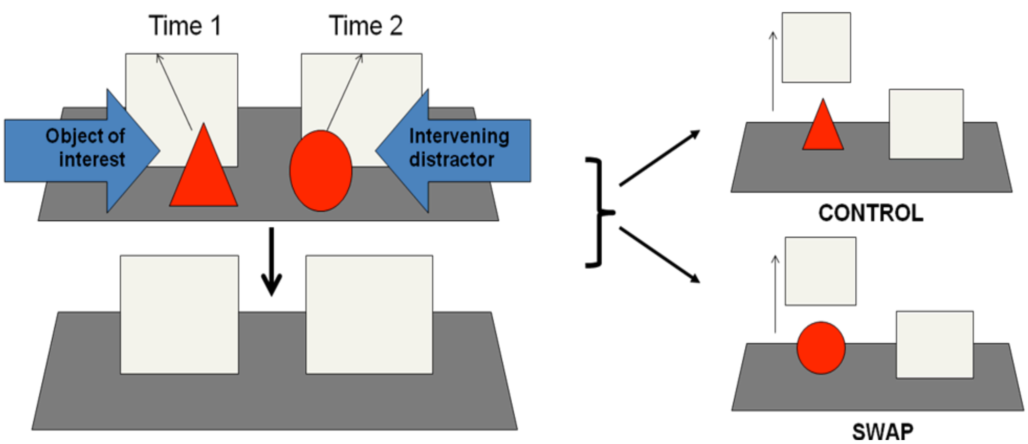


Figure 1: Experimental methods used by Kaldy and Leslie 2003, 2005. In the harder task, infants' memory was probed for the object that was hidden *first*.

Thus, while infants' WM capacity for raw, individuated objects, regardless of feature, stays at about three across the first year of life, WM capacity for features seems to increase over the second half of the first year of life (Table 1). However, while the infant literature suggests a differential development of WM capacity for individuated objects and for features of objects, the results come from studies using vastly different methodologies and stimuli, making it difficult to draw strong conclusions. What exactly is infants' WM capacity for objects and for features, and how does that capacity develop? No research to our knowledge has explicitly measured the developmental time course of WM capacities for objects and for features within a single methodology. The current series of experiments seeks to do just that.

	6-8 months	9-11 months	12-13 months
Raw, individuated objects	3	3	3
Identified objects	1	2	3

Table 1. WM capacity estimates for infants in three age groups for raw, individuated objects (Feigenson, Carey, & Hauser, 2002; Feigenson & Carey, 2003; Wynn, 1992; Wynn, Bloom, & Chiang, 2002) and for identified objects (Kaldy & Leslie, 2003, 2005; Ross-Sheehy, Oakes, & Luck, 2003; Leslie, Tremoulet, & Hall, 2000).

NOTE ON ANALYSIS. This paper includes, in addition to traditional parametric statistics, a probabilistic inference analysis known as Bayes Factor Analysis (Gallistel, in press). In the scope of this paper, Bayes Factor Analysis is a method of computing the odds that two samples came from different distributions. This analysis is useful, because unlike traditional parametric tests where we can only fail to reject the null hypothesis, we can actually give the odds that the null hypothesis is correct. This will prove powerful in Experiment 2, where a null result is obtained.

Bayes Factor is computed by first obtaining the maximum likelihood estimates (MLEs) for the parameters of the probability distributions from which the data are drawn. In the current study, each experiment has two conditions, and thus, two data sets, and two probability distributions. We can think of these two distributions as two hypotheses:

either the data came from one distribution or the other. We compute the likelihood of Hypothesis 1 given the data, and the likelihood of Hypothesis 2 given the data. The ratio of the logs of these likelihoods is Bayes Factor. As Bayes Factor approaches 1, the odds are greater that two data sets are drawn from the same distribution. That is, the odds strongly favor the null hypothesis.

Along with graphs showing mean looking times, MLE probability density functions and cumulative probability density functions are included (see Figures 4, 7, and 8).

Experiment 1: Vanishing objects: Tracking individuals without identification in 6-month-olds

Kaldy and Leslie (2005) showed that 6-month-old infants can only remember the identity of one object, suggesting that they have a WM span of one (see also Ross-Sheehy, Oakes, & Luck, 2003). Yet, studies that have looked at infants' ability to keep track of objects, regardless of identity, have shown that even 6-month-old infants can track up to three objects (e.g. Wynn, 1992). Taken together, these two bodies of literature reveal a contradiction: What exactly is infants' memory span? What is the nature of their mental representation of objects in memory? These lines of research have yielded different estimates of infants' WM capacity because they were measuring different aspects of WM using different methodologies, thus leading to a confusion of "what" and "where".

In the current study, we sought to disambiguate WM for objects and for features within a single methodology. In this methodology, infants are required to keep track of both spatiotemporal and featural information of the objects in question in order to succeed at the task. In a violation-of-expectation task, we asked whether 6-month-old infants remember the existence of a hidden object even if they could not remember the specific identity of the object. That is, even if they are able to remember the specific shape of only the easier-to-remember object, are they nevertheless able to remember that two objects were hidden? This would suggest that infants can individuate the two objects, but discard the featural information for the harder-to-remember object, remembering only that the object exists. However, if they do not remember anything about what went behind the screen, they should have no expectations about what might (or might not) be there, and should not be surprised when they see empty space.

Subjects

Subjects were 17 healthy full-term 5-7-month-old infants (mean age: 6 months, 2 days; SD = 21 days) (nine females). Subjects were recruited from local towns around Rutgers University through phoning lists and advertisements, and received a small gift as compensation. Three additional infants were excluded due to fussiness (1) and experimenter error (2).

Methods

The experiment followed the two-screen violation-of-expectation method of Kaldy and Leslie (2005). Infants were divided into two groups; one group saw the experimental test outcome and one group saw the control outcome (between-subjects design).

Infants were seated on their parent's lap 36 inches away from a 36 X 19X 22 inch stage. At the beginning of the experiment, the experimenter drew the infants attention to the front and back left and right corners and the middle of the stage by jingling bells around her wrist, so that an observer, hidden from the infant's view, watching the infant's face on a monitor could get a sense of the individual infants' eye positions relative to the stage.

The experiment then proceeded with a familiarization phase and a test phase. Throughout the experiment, the experimenter timed her movements to the beat of a metronome which ticked every second. During the familiarization phase, infants saw four trials in which two objects (a disk and a triangle) were placed one at a time on the front of the stage. Infants were allowed to view these objects for four seconds. Then the objects were moved one at a time to the back of the stage in the order in which they appeared initially. Infants were then allowed to view the objects for 10 seconds, after which the experimenter raised the curtain, covering the viewing area. This signified the end of the trial. Order of appearance and side of object placement were counterbalanced across trials.

After the familiarization phase and before the test phase, the experimenter instructed the parent to close his or her eyes so as not to inadvertently influence the infant. The test phase (see Figure 2) also consisted of four trials. At the beginning of each trial, two 7 X 7 inch screens were placed toward the back of the stage. Then, just as in the familiarization phase, two objects were placed one at a time on the front of the stage. After a viewing period of four seconds, the objects were hidden one at a time each behind one of the screens. The experimenter then drew the infants' attention to the screen which occluded the object that was hidden *first* by jingling bells around her wrist. She then raised that screen to reveal either the object that had been hidden there (control condition) or nothing (vanish condition).

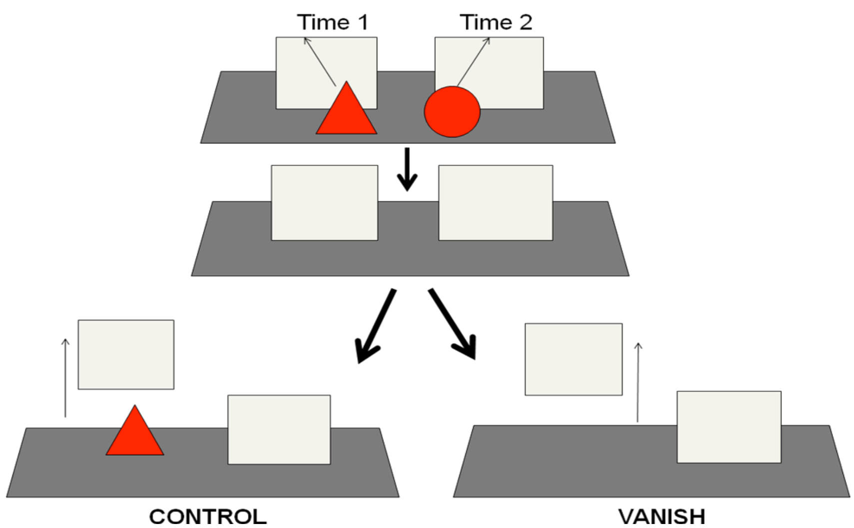


Figure 2: Experiment 1 test conditions. Infant sees two shapes hidden one at a time, then the object hidden at time 1 is revealed to be either the expected object (control) or to have vanished.

The amount of time infants spent looking at the stage after the location was revealed was used as a measure of their expectation about what was in the location. If infants' expectations about what is in the revealed location are violated, they should spend more time looking at the display. An observer who was blind to the condition observed the infant. When the experimenter raised the screen, she signaled to the observer to begin timing. The observer then timed how long infants looked at the display once the location was revealed by holding a button down when the infant was looking at the stage area, and releasing the button when the infant was not looking. When the infant stopped looking for at least two seconds, the stage light went off automatically and the experimenter raised the curtain, hiding the stage and signifying that the trial is over. Looking times were verified by a second observer who rescored the infants' looking time after the experiment; percent agreement was always above 95%.

Results

Infants' looking times were measured for each of the four tests trials. On 8 of the 68 total trials, looking times were considered outlying (greater than or less than two standard deviations from the mean) and were excluded from analysis. Looking times across four trials were averaged for each child, and these scores were averaged to get the group mean.

Five- to 7-month-old infants looked significantly longer at the vanishing outcome (mean: 10.32 seconds; standard deviation: 1.89 seconds) than at the control outcome (mean: 4.02 seconds; standard deviation: 1.50 seconds) (see Figures 3 and 4); ($t = 6.5$; $p = .0001$; Bayes' factor: 129.64:1 against the null hypothesis; the odds favor the alternative hypothesis that the data for the two groups are drawn from different distributions).

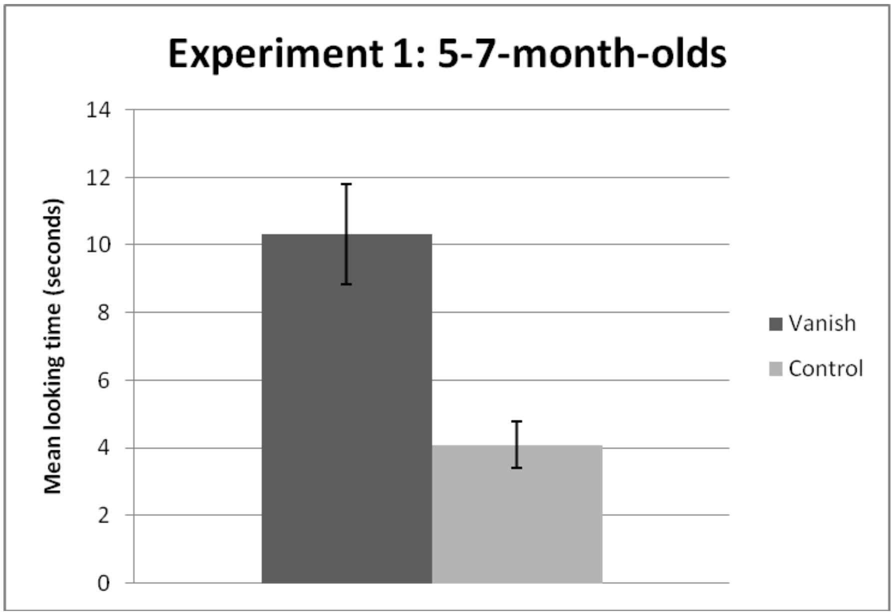


Figure 3: Experiment 1 results with standard error. Infants look significantly longer at the vanish outcome versus the control outcome.

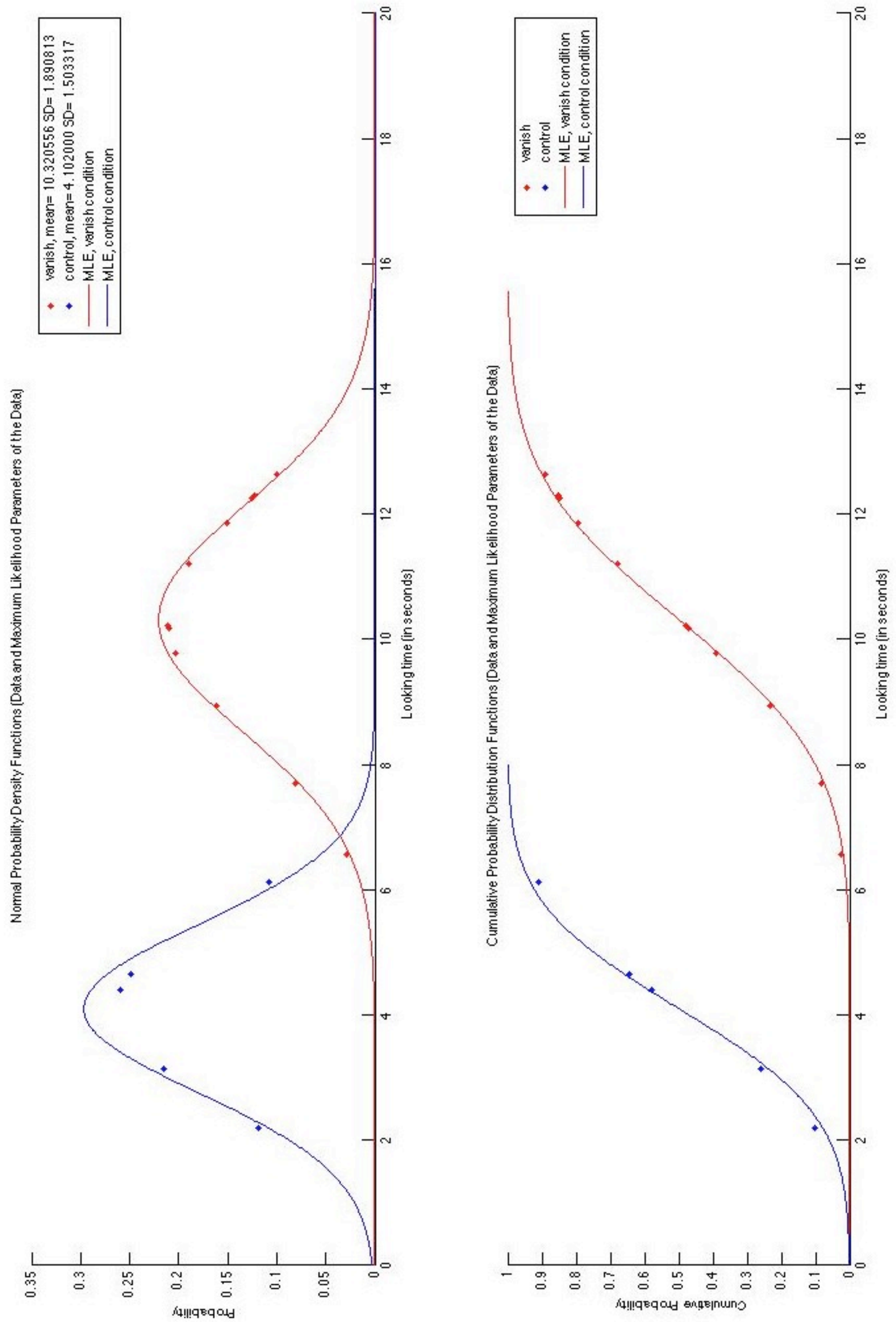


Figure 4. Experiment 1 data and distributions. The top plot displays the normal probability density functions (PDFs) of the data and the PDFs of the maximum likelihood estimates (MLEs) of the parameters of the data. The bottom panel displays the cumulative PDFs and MLEs.

Discussion

Five- to 7-month-old infants looked longer when an object that was hidden behind a screen disappeared, even though a previous study had shown that infants in this age group are not able to remember the specific shape of that object when it is the first hidden of two sequentially hidden objects (Kaldy & Leslie, 2005). The result of Experiment 1 suggests that infants are individuating objects, and are able to maintain representations of at least one object at each location. However, the more recently formed representation (of the last object viewed by the infant) contains more information than the "older" representation; that is, infants recall its shape and its location, while only recalling the location of the first-hidden object. Why do we see this difference in information content across the two object representations?

One possibility is that there is rapid decay of information held in WM. Because the objects are hidden one at a time, a period of about 5 seconds elapses between when infants see the first object hidden and when their memory for that location is tested. During that time, infants watch as the second object is hidden behind its screen and then have their attention drawn to the location where the first object was hidden. If the information held in WM decays rapidly, it is possible that this interval is too long for infants to maintain an informative representation of the identity of the object. However, Kaldy and Leslie (2005) found that infants could maintain WM representations of the easier-to-remember object over longer delays matching the length of time between hiding and revealing the harder-to-remember object. Other studies have also shown young infants' capacity to remember objects over longer delays (e.g. Baillargeon, DeVos, &

Graber, 1989; Baillargeon & Graber, 1988; Luo, Baillargeon, Brueckner, & Munakata, 2003; Rose, Feldman, & Jankowski, 2001).

The result Experiment 1 could provide further evidence that infants' ability to bind featural information to location is not yet mature, and that this ability matures over time. Alternatively, the results also support the possibility that infants have a fixed number of "slots" or "indexes" with which they can represent objects, but that these slots are limited by the information content of the objects. To achieve adult-like capacities, infants' ability to encode information about objects in WM should develop rapidly. In Experiment 2, we tested two age groups, nine-month-olds and 12-month-olds, to see whether we could observe the development of more efficient encoding of information in WM.

Experiment 2: Identified vs. Individuated-and-Different

Up to this point, infancy research has focused on measuring infants' capacity to keep track of *where* objects are or to remember *what* objects are (or what objects are where). In Experiment 1, we found that 6-month-old infants could remember that an object had been hidden behind an occluder, even though Kaldy and Leslie (2005) showed that they had no memory for the specific shape of that object. This implies that when two objects are presented to the infants, and then hidden one at a time, they retain a memory representation of the specific shape of only one of those objects, but remember the *existence* of both objects in their respective locations. Recall that Kaldy and Leslie

(2003) found that 9-month-olds, when presented with the same two-hidden-objects task as the 6-month-olds in Kaldy and Leslie (2005), were able to recall the specific shape of the harder to remember object. In Experiment 2, we asked whether we could observe a development of capacity to recall specific object features by testing 9-month-olds and 12-month-olds.

Eliminating Confounds

Throughout this paper, the distinction has been made between individuated objects and identified objects. Objects with different features shown in different locations to an infant may be individuated by location and not by feature, with no featural information retained in WM. Objects with different features that appear in the same location one at a time may be individuated by feature but not location, with featural information retained in WM. So, individuation can occur with or without identification.

Additionally, a subtle but important distinction that must be considered is that objects may be individuated (by location or by feature) and tagged as *different from* each other with *no specific identifying information* retained in WM. Attempts to assess infants' developing WM capacity for objects have confounded *identified* and *individuated-and-different.* For example, Kaldy and Leslie (2003) devised the two-screen method to test infants' WM for object identities by hiding two objects sequentially behind separate screens, which allowed them to probe memory for individual objects separately. They concluded that 9-month-old infants could remember the identities of up to two objects by testing their memory for the object that was hidden first (that is, the harder to remember of the two items). However, they tested infants memory for the first hidden object by showing them the last hidden object (now unexpectedly behind the first screen). To succeed, infants need only remember that the first hidden object was *different* from the last hidden object, but not the *identity,* the specific shape, of the first hidden object. This confound means that infants need only to recall a subset of the objects presented to them in the task in order to succeed at the task. This confound makes it difficult to pinpoint the underlying constraints on infants' developing WM capacity.

In the next experiment, we asked whether nine-month-old- and 12-month-old infants could in fact recall the specific shapes of two objects when these confounds were eliminated. Because our goal is to measure the development of WM capacity for object identities, and the literature shows a development of that capacity between 6 and 9 months, it is essential to eliminate confounds that might skew capacity estimates. To eliminate confounds, we introduced a third shape and a third location (Figure 5). Adding a third shape allows for a more "difficult" swap to take place; rather than swapping the last-hidden (easier) object and the object in the probed location, we can swap the first-hidden (harder) object and the object in the probed location, such that infants can no longer rely on their WM for the identity of the easier object to succeed.

Thus, in Experiment 2, we sought to get a more accurate estimate of the capacity of WM for infants in these two age groups. If nine-month-olds cannot remember the specific identities of two objects when confounds are eliminated, what does this say about the way infants' object representations develop over the first year? In this case, the difference in performance between Kaldy and Leslie (2003) and our task could indicate a WM representation that goes beyond simple individuation or identification of objects; the representation may hold information that the object is *individuated-and-different* without any specific identifying information. If 12-month-olds are able to recall two object identities, this will give us information about the way these representations develop over time.

Subjects

Subjects were 18 healthy full-term 8-10-month-olds (mean age: 8 months 27 days; SD = 21.5 days) (9 females) and 16 full-term 11-13-month-olds (mean age: 12 months 6 days; SD = 21 days) (9 females). Subjects were recruited in the same manner as on Experiment 1. An additional five infants were excluded due to fussiness (2), parental interference (2), and experimenter error (1).

Methods

The basic design of Kaldy and Leslie (2003, 2005) (Figure 1) was extended by adding a third screen and third shape in order to eliminate confounds (Figure 5). Infants in each age group were divided into two groups; one group saw the experimental outcome and one group saw the control outcome (between-subjects design). All infants were familiarized with three red shapes (a disk, a triangle, and a square). Even though we were only interested in infants' WM capacity for the last two objects hidden, it was essential to present the three objects during familiarization and test, so that the infants would not be presented with a novel object during testing. During familiarization trials, the experimenter placed each shape one at a time on the stage. Infants were allowed to view the shapes for 4 seconds, then the experimenter moved each shape to the back of the stage in the order in which it was initially presented. Infants were then allowed to view the objects for 10 seconds before the curtain was raised to cover the display. Infants saw four familiarization trials with order of shape presentation and position of shape on stage pseudo-randomized.

During the test phase, three screens were placed toward the back of the stage. The experimenter then placed three shapes one at a time on the front of the stage. Infants were allowed to view the shapes for 4 seconds, after which the shapes were moved one at a time behind each screen. The order of the shapes and direction they were placed on the stage (either left-to-right or right-to-left) were counterbalanced across trials. The object that was to be tested was always hidden behind the middle screen. The experimenter then drew infants' attention to the middle screen by jingling bells on her wrist. She then raised the screen to reveal either the unexpected "swap" of the object that was hidden first (the "hardest to remember" object) in the place of the middle object (the one that was hidden second) or the expected object (control condition) (see figure 5).

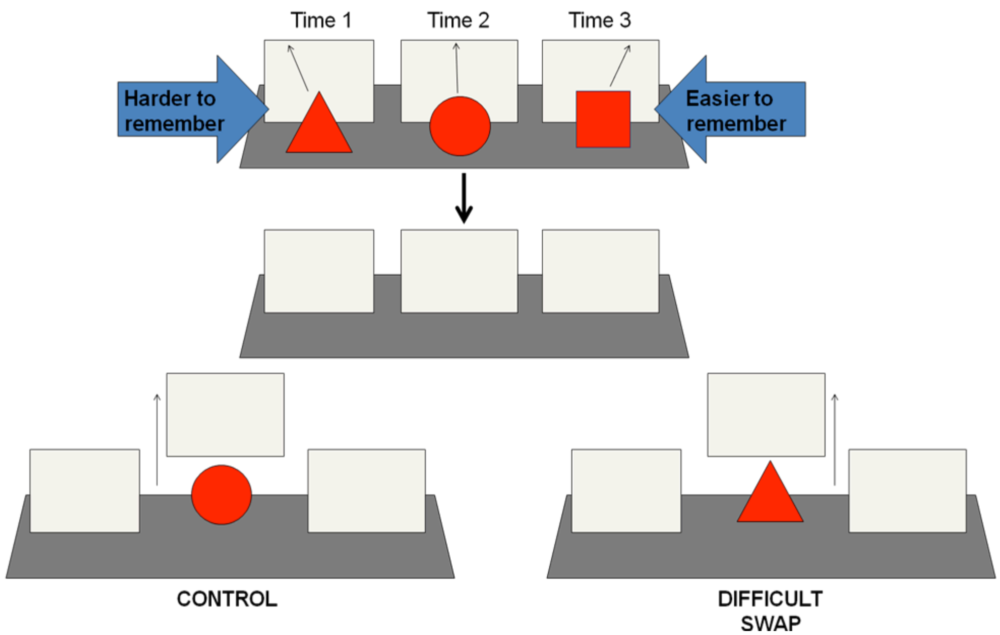


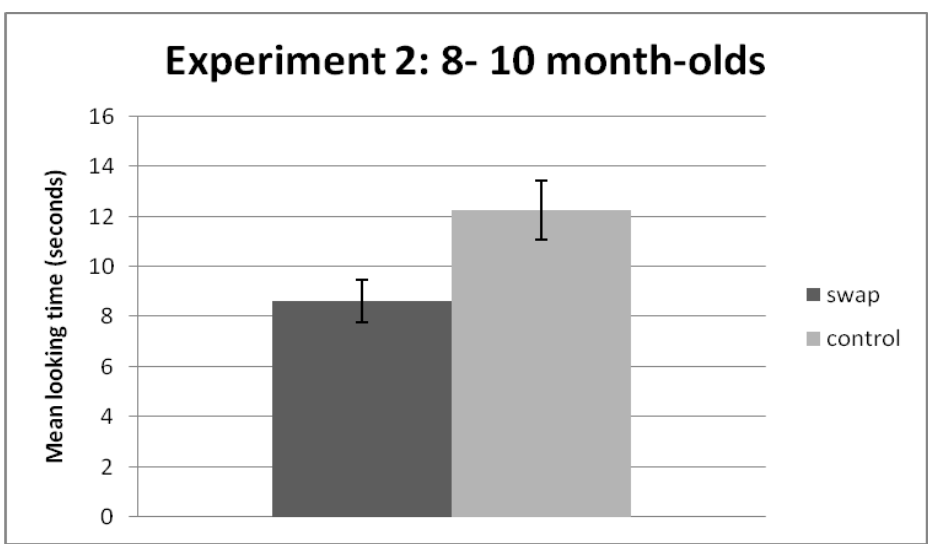
Figure 5: Experiment 2 test conditions. Three shapes are hidden one at a time. Then the object hidden at time 2 is revealed to be either the expected shape (control), or to have swapped places with the object hidden at time 1 (difficult swap).

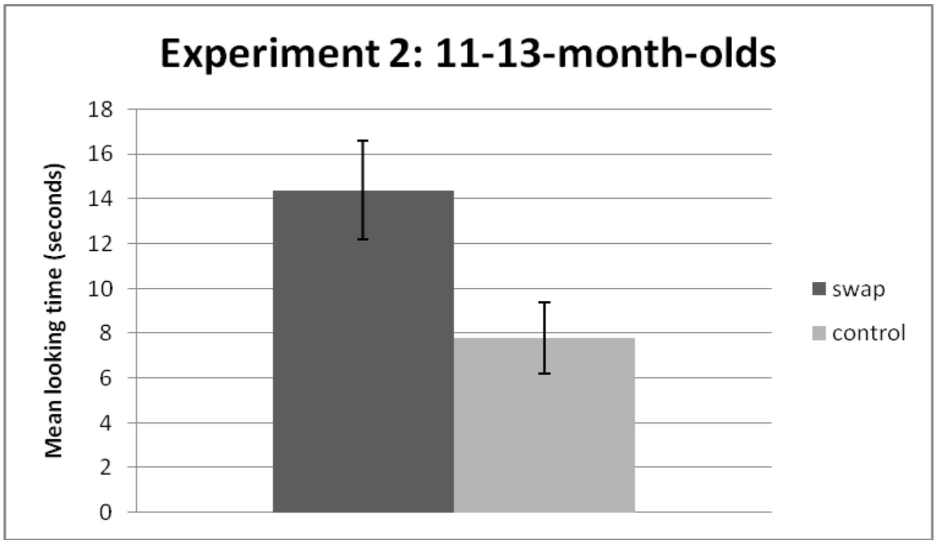
An observer who was blind to the condition timed how long infants looked at the display after the location of the middle object was revealed, as in Experiment 1. When infants stopped looking for at least two seconds, the stage lights went out automatically and the experimenter raised the curtain hiding the stage to signal that the trial was over. Looking times were verified by a second observer who rescored the infants' looking time after the experiment; percent agreement was always above 95%.

Results

Infants' looking times were measured for each of the four tests trials. Outlying times (greater than or equal to two standard deviations from the mean) were excluded from analysis; of the 134 total trials completed by all subjects, 20 trials were removed from analysis. Looking times across four trials were averaged for each child, and these scores were averaged to get the group mean.

Eight- to 10-month olds did not look significantly longer at the swap outcome (mean = 8.63 seconds, standard deviation = 2.23 seconds) versus the control outcome (mean = 9.96 seconds, standard deviation = 3.09 seconds, see Figures 6a and 7) ($t=-0.98$, $p=.34$, two-tailed; Bayes factor = 1.43:1 in favor of the null hypothesis; the odds are that the data were drawn from the same distribution. This is a powerful result: though there is high variability in the data, odds in favor of the null in this case cannot be attributed to lack of statistical power.) Eleven- to 13-month-olds, however, looked significantly longer at the swap outcome (mean= 11.71 seconds, standard deviation= 4.08) that the control outcome (mean= 7.42 seconds, standard deviation= 3.59 seconds, see Figures 6b and 8) ($t= 2.55$, $p= .02$, two-tailed; Bayes factor = 17.28:1 against the null hypothesis; the odds are that the data from the two groups is drawn from different distributions).





Figures 6a and 6b: Experiment 2 results with standard error. 11-13-month-old infants looked significantly longer at the swap outcome, while 8-10-month-olds did not.

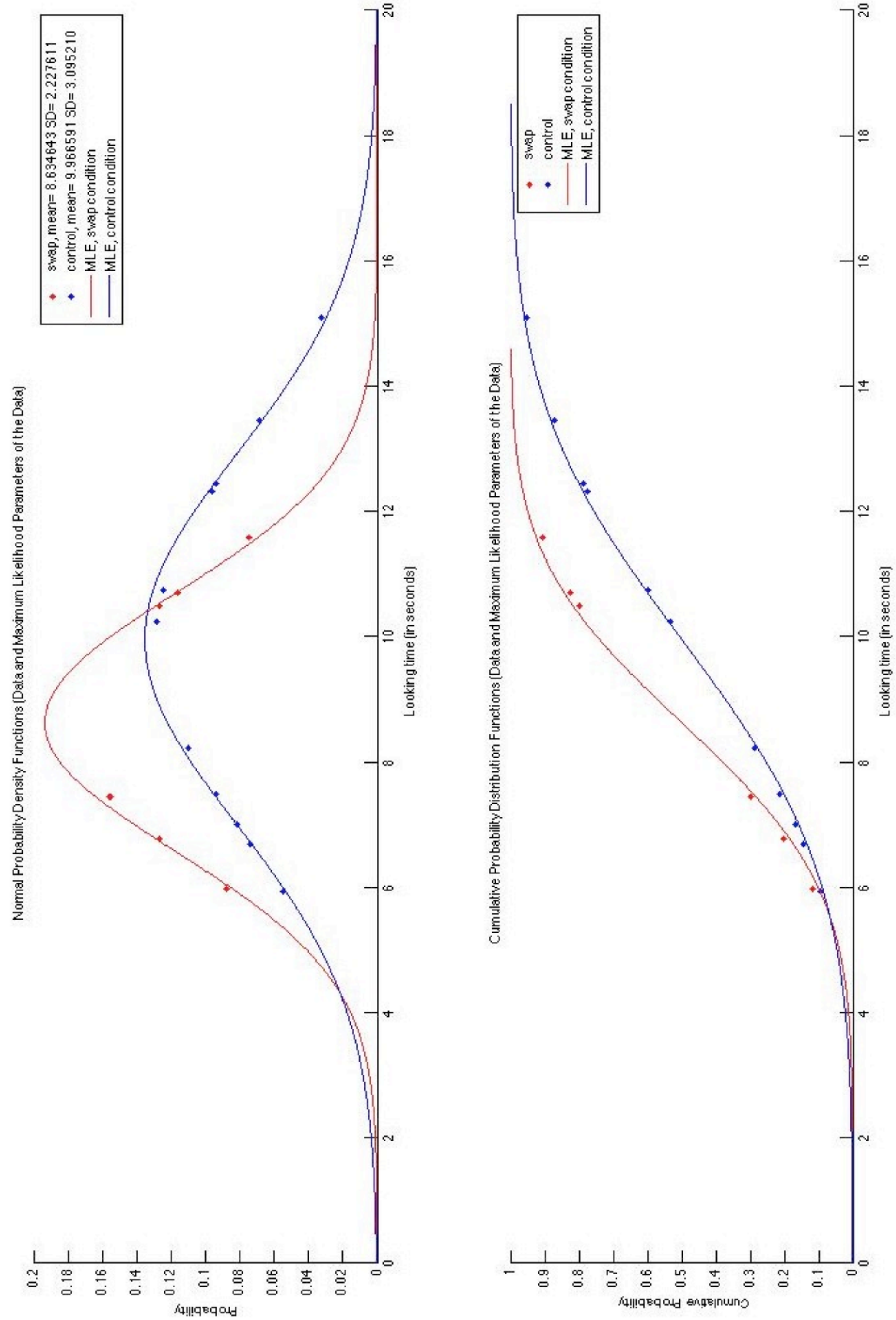


Figure 7: 8-10-month-olds in Experiment 2.

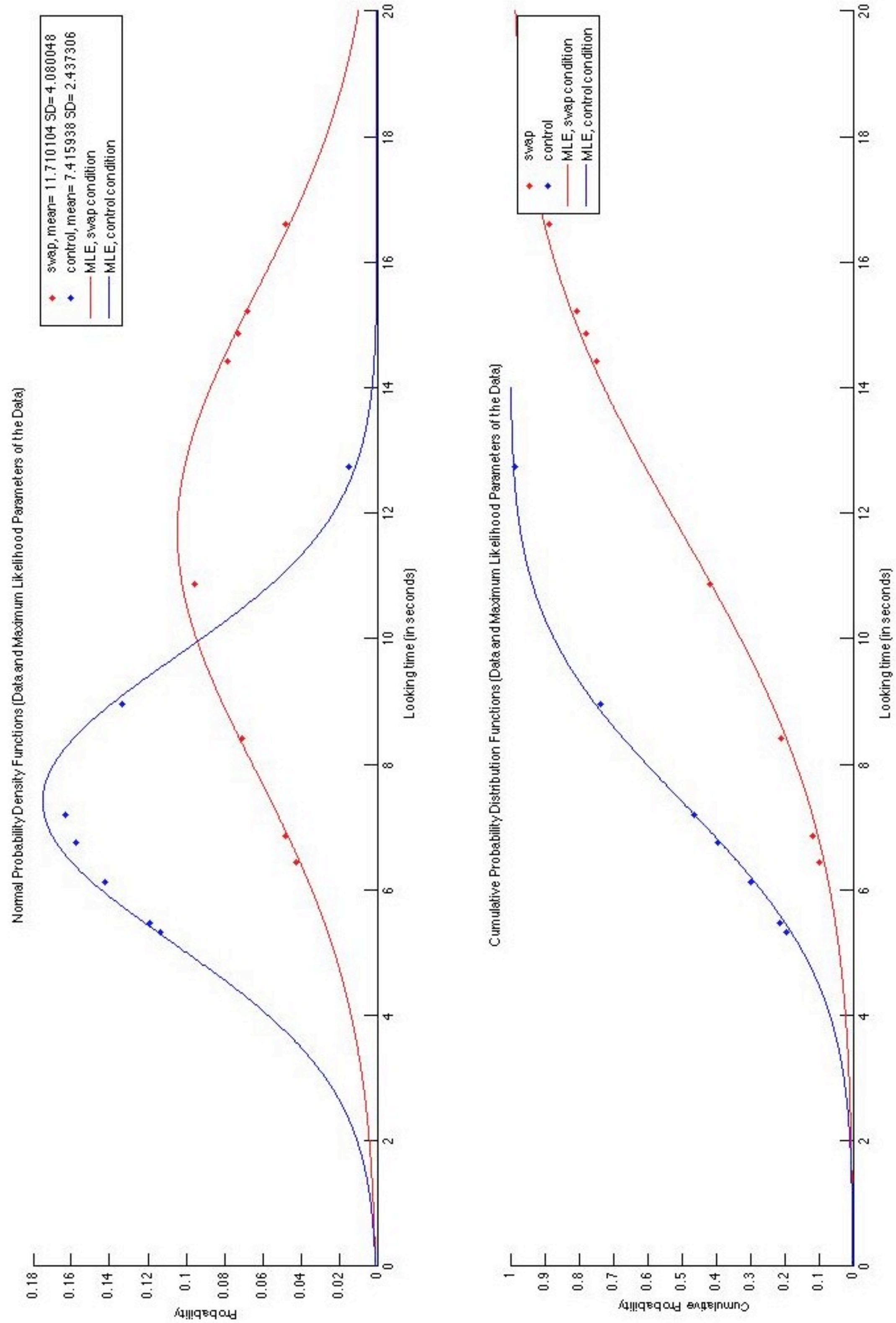


Figure 8: 11-13-month-olds in Experiment 2.

General Discussion

In Experiment 1, we found that 5-7-month olds could remember the existence of an object even if they could not recall its specific identity. In Experiment 2, we controlled for confounds by adding a third shape, making it so infants could not rely on their memory of the last-hidden object to succeed at the task. We found that, when controlling for confounds, 8-10-month-olds could not remember the specific identity of the probed object. Combining this result with the result of Kaldy & Leslie (2003), we can conclude that 8-10-month-olds can remember that the probed object is *different from* the last object that they saw, even if they could not remember the shape. In our study, when infants saw a disk, triangle, and square hidden one at a time in order, and the disk was revealed in the place where the triangle should be, 9-month-olds do not seem to mind. Both the triangle and the disk are *different from* the square. Five- to 7-month-olds do not seem to have this "different from" representation. By contrast, 11-13-month-olds are able to succeed at this task, indicating that they can remember the specific shape of at least two objects (see Table 2).

	5-7 months	**8-10 months**	**11-13 months**
Raw, individuated objects	At least 2	At least 2	At least 2
Shapes	1	1 +	At least 2

Table 2. We confirmed WM limit for shape for 5-7 month-olds while showing that they can recall at least two individuated objects. We failed to find that 8-10-month-olds could recall two shapes, but showed that they can recall more than 5-7-month-olds in that they can remember one shape, plus one "different from that shape" object. Twelve-month-olds can recall at least 2 shapes when controlling for subsampling confounds.

These results indicate a clear development over the second half of the first year of life of WM capacity for object identities (in this case, shapes). But what exactly is developing? This question is of primary concern if our goal is to uncover the nature of object representations in WM. In the current series of experiments, we used very simple stimuli, varying only shape. However, different features have variable impact on individuation and identification. Tremoulet, Leslie, & Hall (2000) found that 12-month-olds were able to individuate *and* identify objects by shape, but were only able to individuate, and not identify, objects by color. While infants are able to use color information when objects are in full view, they are not able to store that information in memory in order to perform the task successfully. It is unclear whether the difference between the colors was as salient to infants as the difference between the shapes. Indeed, Kaldy and Blaser (in press) found that the amount of difference needed for 6.5-month-old infants to notice a color change was much more than the amount needed to notice a shape change, and that the amount of difference needed for both features was less for 9-month-olds than for 6.5-month-olds.

Adult WM

It is possible that infants' capacity to hold features in WM increases over the first year. Recent research into WM in adults has uncovered a greater role for visual information in constraining WM capacity. For example, there is good evidence that adult WM capacity is limited to around four objects, and that this limit seems robust even when the objects are made up of conjunctions of simple features (Luck & Vogel, 1997), which supports

Miller's (1956) original conjecture that WM holds chunks of variable (or perhaps unlimited) capacity. However, Alvarez and Cavanagh (2004) showed that adults' WM capacity decreased as featural complexity of the objects to-be-recalled increased. They suggested that WM may be limited to a fixed number of features as well as a fixed number of objects.

But given that even young infants are able to recall color if the difference between the colors is made salient, a more likely explanation is one that is currently being tested extensively in the adult literature: WM representations may have a variable resolution which can affect recall. For instance, Awh, Barton, and Vogel (2007) found that sample-test similarity limited WM capacity in a change detection task, but that capacity estimates for even the most complex stimuli which had low sample-test similarity were similar to capacity estimates for simple stimuli.

The resolution of WM representations is not fixed. Familiarity with stimuli can bolster WM capacity for those items (Eng, Chen, & Jiang, 2006). Curby and Gauthier (2007), measured the effects of perceptual expertise on memory capacity for upright and inverted faces and cars and found that subjects showed significantly higher capacity estimates for upright stimuli versus inverted stimuli. This effect was stronger for upright faces than for upright cars which the authors interpreted as evidence that faces are subject to a more efficient, holistic encoding process. In a related study, Scolari, Vogel, and Awh (2008) found that it is resolution and not number of objects that can be held in memory that is improved by perceptual expertise. Resolution can also be improved by longer viewing times (Chen, Eng, & Jiang, 2006) and statistical regularities in the visual stimuli (Brady, Konkle, & Alavarez, 2008).

Infants can remember the existence of objects, even if they do not recall the identities of those objects. Evidence from adult fMRI studies indicates different brain areas are responsible for WM for objects and for features of those objects (Xu & Chun, 2006), the former constrained by a fixed number of slots and the latter constrained by a finite pool of cognitive resources, the allocation of which dictates the resolution of the WM representation.

Taken together, the evidence presented in this paper along with the adult literature on WM capacity point to a structure of WM in which individual objects can be represented with some variable amount of information content. This could mean no information about the object, some information, or a high resolution representation preserving much of the information of the object. For infants, it seems likely that it is the ability to efficiently encode featural information, that is, the resolution of WM that develops over the first year, while the ability to store objects with no information content seems to come for free.

Conclusion

The results of the experiments show that, by six months of age, infants have the capacity to encode only a limited amount of information in WM; they are able to keep track of the locations of two objects that they have visually discriminated by feature or location, but are only able to remember the specific shape of the last object they saw. However, infants' ability to efficiently encode the information content of objects increases over the second half of the first year of life. By 12 months, infants are able to remember the specific shape of at least two objects. Infants' capacity to recall *individuated* objects stays the same over the second half of the first year, while capacity to recall *identified* objects increases. Objects that are visually discriminable to infants may not be discriminable in WM with limited resolution, resulting in individuation without identification. As the resolution of infants' WM increases, their recall of object identities improves. This development results in the pattern of infants' performance.

Future research

While the current work uncovers a pattern of development of infants WM, further investigations are needed to develop a less descriptive and more computational model of the developing processes underlying infants' performance on WM tasks. While the current studies looked only at shape, investigating capacities for individual features should be avoided in light of adult and infant literature showing that efficient compression likely plays a significant role. Rather, future investigations will manipulate the information content of displays systematically to find out whether infants can take advantage of information regularities, context, and salience to form more efficient representations and thereby increase their object WM capacity.

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