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EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Tracking what went where across toddlerhood: Feature-location bound object representations in 2- to 3-year-olds' working memory

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Abstract

Two experiments examined the development of the ability to encode, maintain, and update integrated representations of occluded objects' locations and featural identities in working memory across toddlerhood. Sixty-eight 28- to 40-month-old US toddlers (13 Asian or Pacific Islander, 6 Black, 48 White, 1 multiracial; 40 girls; tested between February 2015 and July 2017) tracked the locations of different color beads that were hidden simultaneously (Experiment 1) or sequentially (Experiment 2). Toddlers' ability to reliably store feature-location bound object representations in working memory varied as a function of age, memory load, and task demands. These results bridge a developmental gap between infancy and early childhood and provide new insights into sources of limitation and developmental change in children's early object representational capacities.

Successfully navigating a three-dimensional world requires the ability to keep track of objects around us as they continually move in and out of occlusion. We therefore rely on working memory to maintain representations of objects that are out of view (Cowan, 2016; Kibbe, 2015). Representing occluded objects in working memory with high fidelity means representing *where* objects are hidden and *which* objects are hidden where. For example, imagine a scenario in which a green block is hidden in a basket and a red block is hidden under a box. To successfully retrieve the red block and not the green block, one can bind surface features (i.e., color) to the objects and bind those feature-bound objects to their unique locations in space (Leslie et al., 1998; Wheeler & Treisman, 2002), and then store the resulting representations in working memory. We refer to these representations as feature-location bound object representations.

The number of feature-location bound object representations that can be concurrently stored in working memory is extremely limited in adulthood (to roughly 3–4 objects or so; Cowan, 2001; Saiki, 2003; Wheeler & Treisman, 2002). The process of integrating information about "what" an object is and "where" it is into the object representation requires attentional resources (Treisman & Gelade, 1980; Treisman & Zhang, 2006), since feature and location information are processed in different neural areas (Courtney et al., 1996; Káldy & Sigala, 2004). Storing those feature-location bound object representations in working memory also requires sustaining that attention in order to maintain the integrity of the bound representations in the absence of continual visual input (Cheng et al., 2019a; Mareschal et al., 1999; Wheeler & Treisman, 2002). The ability to control attention also impacts the contents of working memory, allowing an observer to strategically allocate working memory resources to encoding and maintaining representations of task-relevant objects while avoiding interference from other to-be-remembered items or task-irrelevant distractors (Kane & Engle, 2003).

The capacity of working memory to store feature-location bound object representations appears to undergo significant development across infancy and childhood (see Cowan, 2016; Kibbe, 2015, for reviews). Cowan (2016) hypothesized that the development of working memory could be driven by (a) the development of the capacity of attention that can be allocated to encode and maintain the individual items in the to-be-remembered array and/or (b) the development of attentional control that can be deployed to monitor and strategically maintain the contents of working memory in the face of potential interference. However, Cowan (2016) noted a gap in the literature that has made it difficult to pin down the contribution of these different sources of attention to the developmental trajectory of working memory: the majority of research on the development of working memory for has largely been focused on infants under 2 years, using nonverbal tasks that do not require explicit responding (e.g., Káldy & Leslie, 2003, 2005; Kibbe & Leslie, 2011, 2013, 2016, 2019; Oakes et al., 2013; Ross-Sheehy et al., 2003), and on children ages 4 and up, using tasks that involve explicit instruction and explicit responding (e.g., Pailian et al., 2016; Simmering, 2012). Infants and young children differ along many dimensions, and while evidence suggests the capacity of working memory to store feature-location bound object representations is higher in early childhood than in infancy, it is not necessarily the case that continued increases in development can be extrapolated in the intervening developmental time (Berthier et al., 2000; Hood et al., 2000; see Keen, 2003, for review).

One wedge into this question is to study the development of object working memory in 2-year-old children. Two-year-olds bridge a developmental divide between infancy and childhood, because, like infants, they have limited knowledge and language abilities that could be used for recoding strategies (such as counting, spatial language, or explicit verbal recoding) but, like older children, they have the motor skills and receptive vocabulary to make explicit responses. Characterizing object working memory during the toddler years can therefore provide important insights into how attention contributes to developmental change in working memory for feature-location bound object representations. The goal of this paper is to examine the development of working memory for feature-location bound object representations in 2-year-olds.

Previous work suggests a developmental trajectory for feature-location bound object representations in working memory that is characterized by marked increases in the number of feature-location bound object representations that can be maintained in working memory between infancy and early childhood. At 5 months, infants are able to maintain in working memory the locations of two objects hidden in sand, but are not able to integrate features into their representations of those objects (Newcombe et al., 1999; see also Mareschal & Johnson, 2003). By 6 months, infants who observe two different objects hidden in separate locations can maintain in working memory a representation of one of those objects with both "what" and "where" information integrated (Káldy & Leslie, 2005; Kibbe & Leslie, 2016). By around 9 months, infants can maintain integrated feature-location bound representations of both hidden objects (Káldy & Leslie, 2003; Kibbe & Leslie, 2013). At 25 months (but not at 20 months), infants can keep track of the identities of two hidden objects even as their locations move through space (Cheng et al., 2019b), suggesting the robustness of feature-location bound representations in working memory increases significantly across infancy. By 4 years of age, children can reliably maintain in working memory around 3–4 feature-location bound representations (Cheng & Kibbe, 2022; Pailian et al., 2016; Simmering, 2012), and can maintain 4–5 representations by age 5 (Applin & Kibbe, 2020; Simmering, 2012). These results suggest that developmental change in working memory for feature-location bound object representations may be driven by increases in the capacity of attention to encode and maintain these representations in working memory.

However, when children are required to maintain representations in working memory while also encoding and storing additional representations, the developmental picture changes somewhat. This is because encoding and storing additional representations of objects requires dividing attention between maintaining representations already stored in working memory and encoding those additional representations (Kibbe & Leslie, 2013; Moher & Feigenson, 2013; Wheeler & Treisman, 2002). When objects are hidden sequentially, such that infants must encode new representations while also attempting to maintain already encoded representations in working memory, infants remember fewer objects, and show better recognition for the last-hidden objects in an array compared with earlier hidden objects suggesting that they have difficulty effectively dividing attention (Káldy & Leslie, 2003, 2005; Kibbe & Leslie, 2011, 2013, 2016; see Káldy & Leslie, 2005, for an important control study that rules out temporal decay as an explanation). Kibbe and Leslie (2013) also found that 12-month-olds remembered more objects than 9-month-olds in a sequential-hiding task, suggesting developmental increases in attentional control across two time points in infancy. Older children's working memory for feature-location bound object representations is more robust in the face of interference from additional items, suggesting that attentional control may contribute to development beyond age 5 years (Cheng & Kibbe, 2022; Walker et al., 1994). However, older children's working memory also is supported by strategies not available to infants, such as phonological recoding, rehearsal, or semantic knowledge (Dempster, 1981; see Cowan, 2016) and metacognitive awareness of working memory limitations (Applin & Kibbe, 2020), making the contribution of attentional control development to working memory development less clear.

In sum, infant work suggests that the development of working memory may be driven by increases in the attentional resources available to encoding and storing objects, and that attentional control may begin to contribute to working memory development in the second half of the first year of life. Research with older children suggests that attentional control may be a more powerful driving force for developmental change in working memory capacity. How do attentional processes drive development between infancy and childhood?

One way to bridge this divide is to examine the development of working memory for feature-location bound object representations between infancy and early childhood. The toddler period (ages 2–3 years) is characterized by substantial developmental increases in sustained attention (Ruff & Capozzoli, 2003), selective attention (Mash et al., 2003; Veer et al., 2017), attentional control (Gagne & Saudino, 2016; Hendry et al., 2016), and spatial working memory (Jenkins & Berthier, 2014; Morra et al., 2021). Episodic memory, which involves binding contextually dependent what-where-when associations and storing those associations over extended periods, is thought to emerge in the toddler period (Newcombe et al., 2014) and undergoes substantial development during this time (Blankenship & Kibbe, 2022; Liszkai-Peres et al., 2021; Newcombe et al., 2014; Sonne et al., 2017). Research with adults suggests that episodic memory and working memory may rely on shared neural substrates (Cabeza et al., 2002) and recent work has hypothesized that episodic memory may be engaged to support working memory for bound representations (Beukers et al., 2021), potentially supporting developmental change in the capacity of working memory (i.e., the number of feature-location bound objects that can be concurrently maintained in working memory) during this period.

To our knowledge, there has only been one study that examined the development of working memory for feature-location bound representations in children between the ages of 2 and 3 years. In Cheng et al. (2020) task, 24–38 month-olds viewed sets of three "cards" on a computer screen. Each card "flipped over" sequentially to reveal a unique novel image, until all images were simultaneously visible. The cards then all flipped back simultaneously, hiding the images. A cue card was then presented, showing an image that matched one of the hidden cards. The authors measured children's gaze direction toward one of the hidden cards as a measure of children's working memory. To succeed, toddlers needed to remember the spatial locations of specific images, integrating "what" and "where" into their representations at each spatial location on the screen. The authors found that toddlers successfully remembered the locations of the images that were displayed in the outermost positions during encoding. But while toddlers' performance was significantly above chance in their task, it was far from perfect, and the authors observed no developmental increases in toddlers' performance on the task across their age range. These results suggest that the ability to encode and maintain representations of three-object arrays may be an emerging skill in the toddler period, potentially suggesting that the capacity of working memory to store feature-location bound object representations is increasing. Since their task did not make significant demands on attentional control, the role of attentional control in working memory for feature-location bound object representations is still unknown.

The goal of the present research was to characterize working memory for feature-location bound objects in toddlerhood in order to provide new insights into the development of object working memory. Specifically, our task design allowed us to manipulate working memory load (the number of objects to be remembered) and the top-down attentional demands of the task (the extent to which children needed to maintain feature-location bound representations in working memory while also encoding new representations, effectively dividing attention between working memory maintenance and encoding) and to examine how these demands impacted task performance in 2- to 3-year-olds. We adapted the object working memory task of Applin and Kibbe (2020) to be suitable for 28- to 40-month-old children. Children observed different color beads hidden in separate locations. Children were then shown a color on a cue card and were asked to find the location of the bead that matched the color on the card. This task has the advantage of paralleling infant looking-time tasks (e.g., Káldy & Leslie, 2003, 2005; Kibbe & Leslie, 2011, 2013, 2016, 2019) in that children observe sets of real, three-dimensional objects that differ along a single featural dimension (color) moving into occlusion, either simultaneously or sequentially. Thus, the task makes similar demands on attention and feature-binding processes as the infant tasks outlined above (see Kibbe, 2015, for a review and task analysis). However, unlike infant looking time tasks, our task requires children to give an explicit response over repeated trials, which makes the task more similar to tasks with older children and adults (and makes the task more engaging for toddlers).

In Experiment 1, we examined how many feature-location bound object representations toddlers could maintain in working memory, and examined whether toddlers' capacity for maintaining feature-location bound object representations increased across this age range by examining toddlers' performance on the task as a function of their age in months. We showed toddlers sets of two or three different-color beads—such that the entire array was visible at encoding—and then hid the beads simultaneously. While a previous study examining 2- to 3-year-olds' working memory for three-object arrays did not reveal developmental increases in toddlers' capacities Cheng et al., 2020), testing 2-year-olds with a lower memory load (two objects) in addition to a higher memory load (three objects) could potentially reveal developmental increases at lower loads, where capacities may be more well established (Blankenship & Kibbe, 2022; St. John et al., 2019).

In Experiment 2, we examined toddlers' ability to maintain feature-location bound object representations while also encoding new object representations in working memory, which engages attentional control, and examined the development of this ability across this age range by examining toddlers' performance as a function of their age in months. Experiment 2 was similar to Experiment 1, except objects were hidden sequentially instead of simultaneously—children had to encode object-feature-location bindings in working memory while maintaining already-encoded representations in working memory, requiring the division of attention between encoding and maintenance. Since toddlerhood is characterized by substantial increases in attentional control, we examined how 2-year-olds allocated attention during this demanding task, and whether and to what extent we would observe the developmental change in their ability to maintain representations while encoding new representations.

Our experimental design also allowed us to examine the kinds of errors children made. On each trial, objects were hidden in an apparatus that contained six potential hiding locations, such that some locations were occupied by a bead and some were empty. Because children were asked to point to the location of a specific hidden bead when prompted, we could look at whether children selected an occupied but incorrect location (suggesting a feature-binding error) or an empty location (suggesting failure to track the locations of the objects on that trial), giving us insights into how our task manipulations may impact children's object representations stored in working memory.

EXPERIMENT 1: SIMULTANEOUS PRESENTATION

Method

Participants

Thirty-four children (M_{age} = 34.69 months; range 28.17–40.6; 21 girls) participated in the laboratory at Boston University. The sample size was determined by a power analysis using G*Power 3.1 for a planned repeated-measures ANOVA with Set Size, Block Order, and Age as factors, with $\alpha = .05$, $1-\beta = .8$, and assuming a medium effect size ($f = .25$). Children were reported by their parents as Asian (7), Black (3), or White (24). Of these children, 1 was reported as being Hispanic/Latinx. Thirty-three of the 34 participants came from households with at least one parent who had a college degree or higher. Nine additional children were tested but excluded from analysis due to video malfunction (2), touching the objects during test trials (1), or declining to complete the task (6). Data were collected between March 2015 and February 2017.

Participants were recruited through publicly available birth records and from family events in the Boston area. Children were given a small gift for their participation. The Boston University Institutional Review Board approved both Experiments 1 and 2. Informed consent was obtained from all caregivers prior to the start of the study.

Materials

Materials consisted of a black foam core box (11.5 × 57.5 × 18 cm) that was open in the front to show six identical 12 oz. red plastic cups embedded in the box. Above each of the six cups was a circular opening where objects could be deposited. The cups served as separate hiding locations for 2.5-cm plastic beads (yellow, green, blue, red, or purple) that were hidden by the experimenter on each trial. A black bar fastened to a piece of black felt was used to cover the openings all at once. Six brown felt circles attached to the black felt cover marked the locations of each of the openings. Five different color cards, each corresponding to one of the colored beads, were used to probe children's recall for the location of the hidden beads. Figure 1 shows examples of the materials used in Experiment 1. Two cameras captured children's actions (one angled from above and one to the left of the child). Videos were digitally mixed and recorded for later coding.

Procedure

Children were seated at a small child-sized table across from the experimenter in a quiet laboratory room. Children completed a color-matching warm-up trial, followed by a set of practice trials, and finally a set of test trials.

Color-matching warm up

We first familiarized children with the process of matching a color card to a corresponding bead. The experimenter placed 3 different color beads on the table and said, "See these beads? See the different colors?" The experimenter then showed the children three corresponding color cards and said, "And see these cards? See how they have different colors like the beads?" She then flipped all the cards face down, turned one of the cards face up, and asked, "Can you show me which bead matches this card?" Children were encouraged to point to a bead. When children chose correctly, the experimenter picked up the bead, held it next to the card and said, "Great job! See, it's a match!" This procedure was repeated for the other two beads. All children successfully matched all three beads. The experimenter then removed the cards and beads from the table.

Practice trials

Next, the experimenter introduced children to the bead box. The experimenter explained, "Now we're going to play a game. I'm going to hide these beads in these cups

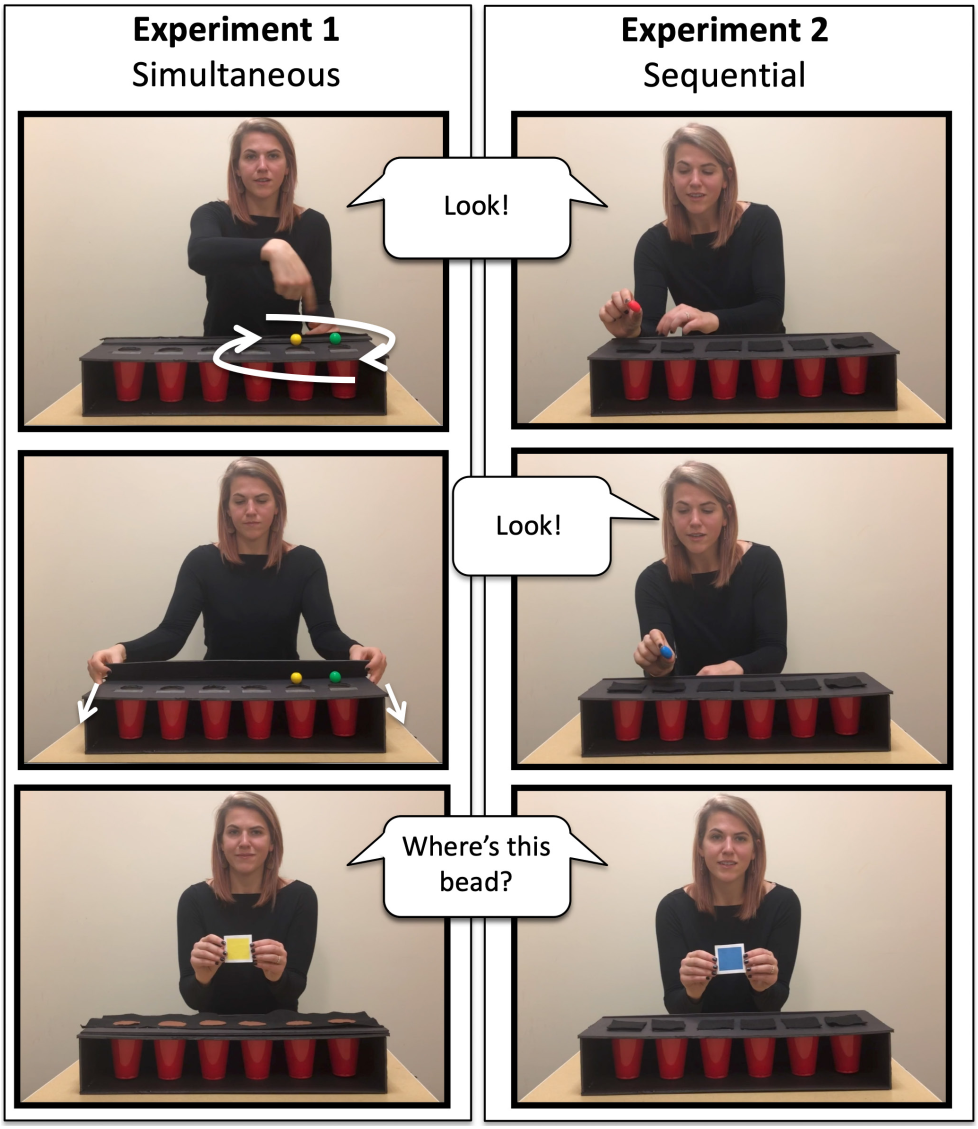

FIGURE 1 Example test trials from Experiment 1 (left panel) and Experiment 2 (right panel). The left panel shows a set size 2 trial from Experiment 1, in which two different color beads were hidden simultaneously and children were asked to recall the location of the yellow bead. The right panel shows a set size 2 trial from Experiment 2, in which two different color beads were hidden sequentially, and children were asked to recall the location of the last-hidden (blue) bead. Children were given feedback after each trial.

and you have to remember which bead is hiding in each spot. Okay? Let's try one!" The experimenter used both hands to simultaneously place two beads on top of the box, each behind an opening but in front of the felt bar. Beads were always placed in locations adjacent to each other on one of the far sides of the box, and were placed either in the two leftmost locations or the two rightmost locations, counterbalanced across trials. The experimenter then drew children's attention to the beads by circling her finger around the array and saying, "Look!". The entire array was visible for ~3 s. The experimenter then dragged the felt bar toward the front of the box, knocking the beads into their respective cups and covering all of the cups at once. After ~2.5 s, the experimenter showed children a color card that matched one of the beads and asked, "Where is this bead?" Once children pointed to a location, the experimenter retrieved the bead in that location. Children were given feedback on each practice trial. If they were correct, the experimenter said, "Great job!" If they were incorrect, the experimenter said, "Whoops that's not it!" and retrieved the correct bead, saying, "Here it is!" The experimenter then removed the remaining bead and said, "All these cups are empty now. Let's play again!"

This procedure was repeated for a second practice trial. The experimenter again hid two beads of different colors (on the opposite end of the box to the previous trial to minimize proactive interference across trials), prompted children to point to the location of one of them, and gave children feedback as to whether they were right or wrong. Children received a score of 1 on trials where they were correct and a score of 0 when they were incorrect. Sixteen of 34 children chose the correct location on the first practice trial, and 19/34 chose correctly on the second practice trial.

Test trials

Children completed two blocks of Test trials, a Set Size 2 block and a Set Size 3 block, with block order counterbalanced across children. Set Size 2 trials proceeded identically to practice trials. Each participant completed a total of four Set Size 2 trials, with children's recall of objects in each position (right object, left object) probed twice (see Figure 1 for an example Set Size 2 trial). Set Size 3 trials proceeded similarly, except that a third bead was hidden. The timing of the display and hiding events were the same as in Set Size 2: a ~3 s encoding period followed by a ~2.5 s maintenance period. Each participant completed a total of six Set Size 3 trials, with children's recall of the objects in each position (right, middle, or left object) probed twice. Eighteen participants completed the Set Size 2 block first and 16 participants completed the Set Size 3 block first. Feedback was given on all trials, as in the practice trials.

Children's responses were later coded from video by two independent observers. On each trial, children's responses were coded as "1" (correct) or "0" (incorrect). There were no disagreements between the coders.

Results

Analyses for Experiments 1 and 2 were planned prior to data collection.

We first conducted a repeated-measures ANOVA on children's mean proportion correct across trials at each Set Size, with Set Size (2 or 3) as a within subjects factor, Block Order (Set Size 2 Block first or Set Size 3 Block first) as a between subjects factor, and Age (in months) as a covariate. We observed a main effect of Age (F[1, 31] = 10.25, p = .003, η^2_p = .248) and an Age × Set Size interaction (F[1, 31] = 5.09, p = .031, η^2_p = .141). These effects are illustrated in Figure 2. Children's performance on Set Size 2 trials increased with age, while their performance on Set Size 3 trials remained relatively flat across our age range. We observed no main effect of Block Order (F[1, 31] = 0.58, p = .452, η^2_p = .018) or Set Size (F[1, 31] = 2.92, p = .098, η^2_p = .086), and no Set × Block Order interaction (F[1, 31] = 3.65, p = .065, η^2_p = .105).

We next examined whether children's performance on Set Size 2 trials was correlated with their performance on Set Size 3 trials. That is, we asked whether children who show better recall for the objects in the two-object array also show better recall for the objects in the three-object array. We found that children's mean proportion correct on Set Size 2 trials was significantly correlated with their mean proportion correct on Set Size 3 trials (r = .466, p = .006), and this correlation held when controlling for children's age (r = .385, p = .027), suggesting stable individual differences in children's working memory for feature-location bound object representations.

Previous work suggested that children may prioritize encoding objects based on their spatial locations (e.g., remembering the outermost objects better than the middle object in an array of three objects; Cheng et al., 2020). We, therefore, asked whether children's performance varied as a function of the location of the probed object. For Set Size 2 trials, children were probed to recall either the location of the object hidden in the outermost location or the location of the object hidden second from the end (the innermost object). For Set Size 3 trials, children were probed to recall either the location of the outermost object, the object second from the end (the middle object), or the object third from the end (the innermost object). We, therefore, conducted separate repeated measures ANOVAs at each Set Size with Probed Object Location as a within subjects factor. Based on the results of the overall analysis of children's performance

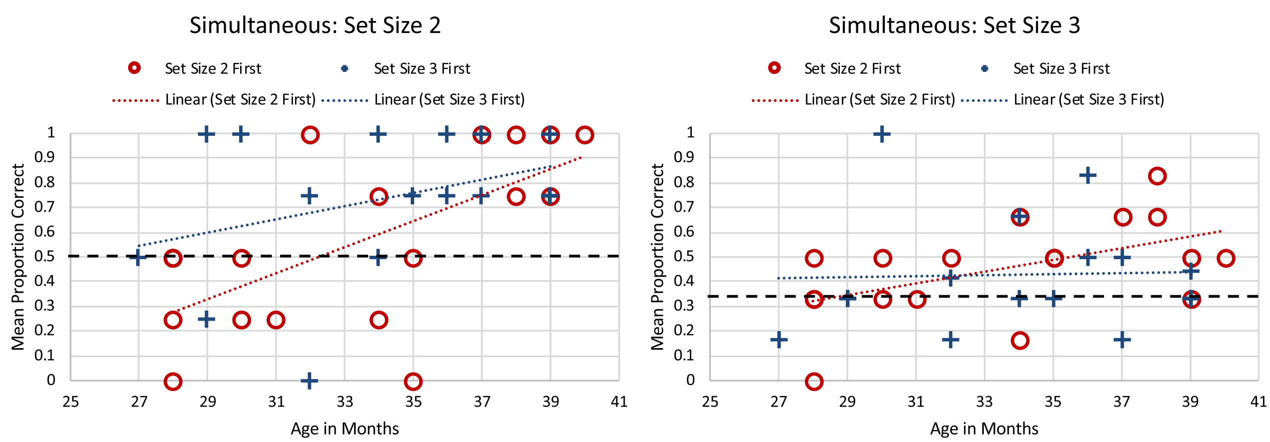

FIGURE 2 Individual children's mean recall accuracy in the set size 2 block (left panel) and the set size 3 block (right panel) as a function of block order (set size 2 first = red circles; set size 3 first = blue crosses) in Experiment 1. Black dashed lines show chance levels for set size 2 (.5) and set size 3 (.33).

presented above, we retained Age (in months) as a covariate, and dropped Block Order as a between subjects factor. For Set Size 2, we observed no main effect of Probed Object Location (outermost or innermost; $F[1, 32] = 0.21$, $p = .651$, $\eta_p^2 = .006$), a significant main effect of Age ($F[1, 32] = 12.13$, $p = .001$, $\eta_p^2 = .275$), and no interaction between Probed Object Location and Age ($F[1, 32] = 0.36$, $p = .553$, $\eta_p^2 = .011$). For Set Size 3, we observed no main effect of Probed Object Location (outermost, middle, or innermost; $F[2, 64] = 0.16$, $p = .853$, $\eta_p^2 = .005$) or Age ($F[1, 32] = 2.74$, $p = .108$, $\eta_p^2 = .079$) and no interaction ($F[2, 64] = 0.22$, $p = .803$, $\eta_p^2 = .007$). These results suggest that the position of the object did not impact children's performance on the task.

Next, we asked to what extent children's performance exceeded what would be expected by chance. Since chance levels varied with Set Size, we conducted a series of one sample t-tests comparing children's mean performance to chance levels at each Set Size (0.5 for Set Size 2; 0.33 for Set Size 3), with α set to .025 to account for two comparisons. Children's mean proportion correct was significantly above chance at Set Size 2 ($M = .65$, $SD = .33$, $t[33] = 2.58$, $p = .014$, $d = .442$) and at Set Size 3 ($M = .44$, $SD = .21$, $t = 3.05$, $p = .005$, $d = .523$), suggesting that, overall, children were tracking the locations of the color beads, and not simply guessing on the task. Children's mean proportion correct on Set Size 2 trials was significantly correlated with their age in months ($r = .524$, $p = .001$), and inspection of Figure 2 shows that above-chance scores were more common in older children. There was no correlation between children's mean proportion correct and their age in months at Set Size 3 ($r = .154$, $p = .384$), and inspection of Figure 2 shows a fairly even distribution of above-chance scores across the age range.

Finally, we investigated the nature of children's errors. We coded whether children who made errors (defined as selecting a location that did not contain the target color bead) chose a location that contained a bead, or whether they selected an empty location. If they selected an empty location, we looked at how far removed that location was from the occupied locations on that trial. On Set Size 2 trials, children made errors on 46/136 total trials. Children selected the incorrect but occupied location (that is, the unprobed bead's location) on the majority of those trials (33/46 errors), and selected an empty location on the remaining 13 trials. Of those 13 trials, children selected the empty location immediately adjacent to the occupied locations on 11 trials, and selected a location further away on the remaining two trials. Results were similar for Set Size 3 trials: children made errors on 113/204 trials, and the majority of those errors involved children selecting an incorrect but occupied location (100/113 total trials). When children selected an empty location, they most often chose the location immediately adjacent to the hidden array (11/13 total trials). Together, these results suggest that, overall, children attended to the locations of the hidden objects on each trial, and when they made errors, they selected the location of another object in the array rather than choosing a location at random.

Discussion

In Experiment 1, we asked 28- to 40-month-old toddlers to track the locations of two or three colored beads that were presented and hidden simultaneously. To succeed, children needed to maintain in working memory bindings between features and objects' locations and to recall and report on the location of an object when probed with a feature (color). We found that, overall, children could recall the locations of hidden objects at above-chance levels when two or three objects were hidden, suggesting that children can maintain feature-location bound representations of at least three objects in working memory. Examination of children's errors suggested that, when children chose incorrectly, they typically chose a location that contained an object (rather than a random location), suggesting that they tracked the locations of the objects, but may not have successfully bound features to the objects (see e.g., Cheng et al., 2020; Kibbe & Leslie, 2013).

We also observed developmental change in these children's ability to maintain feature-location bound objects in working memory. Specifically, children's performance increased with age when they were tasked with remembering feature-location bindings of two occluded objects, but we observed no relationship between age and performance when children were tasked with remembering three objects. This suggests that children's capacity for maintaining two feature-location bound object representations in working memory may be increasing during this period, while their capacity for maintaining more than two objects may be just emerging. These results dovetail with other work showing continued increases in children's capacity to maintain the locations of feature-bound objects in working memory, from 1–2 objects earlier in infancy (Kibbe & Leslie, 2011, 2013) to 3–5 objects later in childhood (e.g., 4–6 years; Applin & Kibbe, 2020; Cheng & Kibbe, 2022; Pailian et al., 2016; Simmering, 2016).

Experiment 1 presented children with arrays of objects which were visible and occluded simultaneously, allowing children to observe the entire array before encoding and maintaining representations of the objects in working memory. In Experiment 2, we presented and occluding objects one at a time, such that children had to divide attention between maintaining working memory representations for earlier-hidden objects and encoding representations of newly presented and hidden objects. We asked whether and how children would prioritize encoding these objects as a function of the serial positions of the objects and the number of objects hidden, and whether we would observe the developmental change in toddlers' abilities to effectively divide attention across our age range.

EXPERIMENT 2: SEQUENTIAL PRESENTATION

Method

Participants

A new group of 34 children (M_{age} = 34.63 months; range 28.2–40.73; 19 girls) participated in the laboratory at Boston University. Children were reported by their parents as Asian (5), Black (3), Pacific Islander (1), White (24), or other (1). Of these participants, one was Hispanic/Latinx. All participants came from households with at least one parent who had a college degree or higher. An additional eight children were excluded due to parental interference (1), declining to complete the task (4), repeatedly selecting the same location on each test trial regardless of where the objects were hidden (1), or touching beads during test trials (2). Data were collected between February 2015 and July 2017. Participants were recruited through publicly available birth records and from family events in the Boston area and were given a small gift for their participation.

Materials

Materials were the same as in Experiment 1 with the following exception: The openings on the top of the box were covered in six individual pieces of black felt that could be lifted and lowered individually (see Figure 1).

Procedure

The procedure was similar to Experiment 1 with the following exception: In both Practice trials and Test trials, beads were hidden one at a time. The experimenter held a bead between her thumb and forefinger above the first cup location, and said, "Look!" before using her other hand to lift the felt flap and deposit the bead in the cup. Each bead was visible to children for ~1.5 s (as defined as the length of time from when the bead was held above its cup location until when the bead was deposited into the cup). She then repeated this procedure for each subsequently hidden bead. Once the final bead was hidden, after ~2.5 s the experimenter showed the children a color card that matched one of the beads and asked, "Where is this bead?" See Figure 1 for an example Set Size 2 trial.

On all trials beads were hidden sequentially starting from the far end of the box (either right or left, counterbalanced across trials) so that the first hidden bead was always in the outside cup, then any subsequently hidden beads were placed in the adjacent cups moving inward. Children first completed two practice Set Size 2 trials (17/34 children chose correctly in the first practice trial, 18/34 chose correctly in the second practice trial). Each participant then completed a total of four Set Size 2 trials, with each Serial Position (first-hidden and last-hidden object) probed twice, and six Set Size 3 trials, with each Serial Position (first-hidden, second-hidden, or last-hidden object) probed twice. Due to a counterbalancing error, there was a slight imbalance in the way children were assigned to block order: 24 participants completed the Set Size 2 block first, while 10 participants completed the Set Size 3 block first.

Two independent observers coded children's responses as correct (1) or incorrect (0). There were no disagreements between the observers.

Results

As in Experiment 1, we first conducted a repeated measures ANOVA on children's mean proportion correct across trials within each Set Size, with Set Size (2 or 3) as a within subjects factor, Block Order (Set Size 2 Block first of Set Size 3 Block first) as a between subjects factor, and Age (in months) as a covariate. These factors are illustrated in Figure 3. This analysis revealed no main effect of Set Size (F[1, 31] = 0.10, p = .759, η^2_p = .003), no main effect of Age (F[1, 31] = 0.44, p = .511, η^2_p = .014), and no Set Size × Age interaction (F[1, 31] = 0.26, p = .611, η^2_p = .008). We did observe a main effect of Order (F[1, 31] = 7.20, p = .012, η^2_p = .189). The interaction between Order and Set Size did not reach statistical significance (F[1, 31] = 4.08, p = .052, η^2_p = .116). The correlation between children's performance on Set Size 2 and Set Size 3 trials also did not reach statistical significance (r = .332, p = .055), even after controlling for age (r = .329, p = .062).

Next, we examined how sequential presentation may have impacted children's recall performance. We computed children's mean proportion correct on trials in which they were probed on the object that was hidden *first* or *last* (Set Size 2 trials) or *first, second*, or *last* (Set Size 3 trials). We then conducted separate repeated measures ANOVAs at each Set Size, comparing children's mean proportion correct at each Serial Position. Based on the results of the overall analysis of children's performance presented above, we retained Block Order as a between-subjects factor, but dropped Age (in months) as a covariate.

For Set Size 2, we observed a main effect of Serial Position (*first-* or *last-hidden*; F[1, 32] = 7.90, p = .008, η^2_p = .198), a main effect of Block Order (Set Size 2 first or Set Size 3 first; F[1, 32] = 9.76, p = .004, η^2_p = .234), and an interaction between Serial Position and Block Order (F[1, 32] = 6.65, p = .015, η^2_p = .172). Figure 4, top panel, illustrates these results. We followed up this analysis with comparisons against chance at each Serial Position for each Block Order (α = .013 to correct for four comparisons). Children who completed the Set Size 2 block first selected the correct location for the probed object at

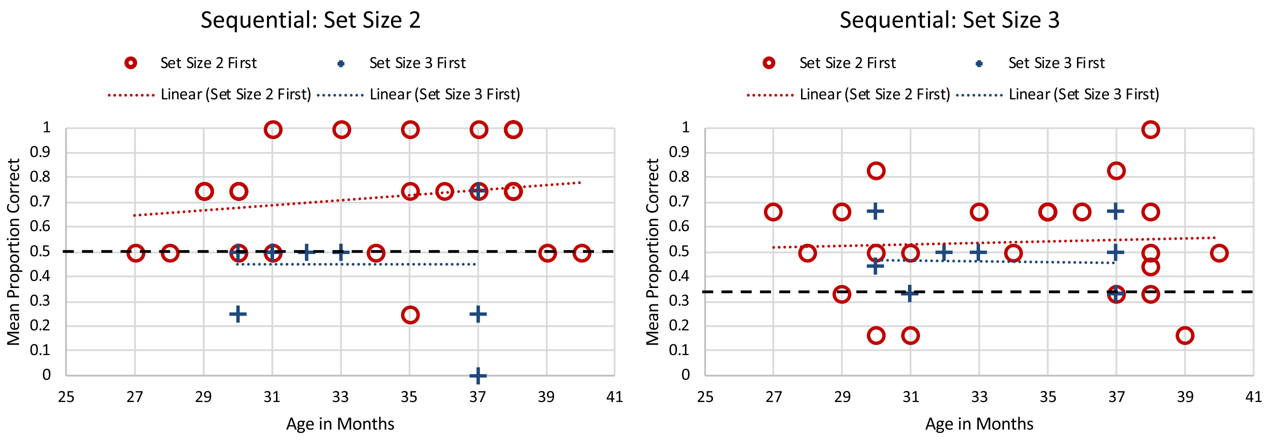

FIGURE 3 Individual children's mean recall accuracy in the set size 2 block (left panel) and the set size 3 block (right panel) as a function of block order (set size 2 first = red circles; set size 3 first = blue crosses) in Experiment 2. Black dashed lines show chance levels for set size 2 (.5) and set size 3 (.33).

rates significantly above chance for both the first-hidden (chance = 0.5; $t[23] = 3.12$, $p = .005$, 95% CI [.07, .35]) and last-hidden ($t[23] = 3.82$, $p < .001$, 95% CI [.11, .35]) objects. Children who completed the Set Size 3 block first appeared to prioritize the last-hidden object in the Set Size 2 block, although their recall performance for this object did not exceed chance levels ($t[9] = 1.81$, $p = .104$, 95% CI [−.05, .45]). These children's recall for the location of the first-hidden object was slightly but not significantly lower than chance levels ($t[9] = -2.43$, $p = .038$, 95% CI [−.55, –.02]).

For Set Size 3, we observed a main effect of Serial Position (*first*-, *second*-, or *last*-hidden; $F[2, 64] = 55.05$, $p < .001$, $\eta_p^2 = .632$), no main effect of Block Order (Set Size 2 first or Set-Size 3 first; $F[1, 32] = 1.12$, $p = .297$, $\eta_p^2 = .034$), and a significant Serial Position × Block Order interaction ($F[2, 64] = 11.36$, $p < .001$, $\eta_p^2 = .262$). Figure 4, bottom panel, illustrates these results. We again followed up this analysis with comparisons against chance at each Serial Position for each Block Order ($\alpha = .008$ to correct for six comparisons). Children who completed the Set Size 2 block first prioritized the first- and last-hidden objects, correctly identifying the location of the probed object at rates significantly above chance (chance = 0.33; first-hidden: $t(23) = 4.33$, $p < .001$, 95% CI [.16, .46]; last-hidden: $t(23) = 7.31$, $p < .001$, 95% CI [.35, .62]). Children's recall for the second-hidden object was overall somewhat lower than chance levels, although the significance level did not fall below our strict criterion ($t(23) = -2.83$, $p = .009$, 95% CI [−.28, –.04]). By contrast, children who completed the Set Size 3 block first prioritized the last-hidden object: all 10 children selected the correct location when probed to locate the last-hidden object in all Set Size 3 trials, but failed to select the correct location at rates above chance when probed to locate the first- ($t[9] = -1.92$, $p = .087$, 95% CI [−.32, .03]) or second- ($t[9] = -1.59$, $p = .146$, 95% CI [−.31, .05]) hidden objects.

Finally, as in Experiment 1, we investigated the nature of children's errors (see Experiment 1, methods, for coding scheme). On Set Size 2 trials, children selected an incorrect location when probed on 49/136 trials. On a little over half of those trials (28/49), children selected the other occupied but incorrect location (e.g., the location of the unprobed bead) and selected an unoccupied location on the remaining 21/49 trials. The distributions of children's errors differed as a function of Block Order. Children who completed Set Size 2 trials first more often selected an occupied but incorrect location (17/27 trials) than an empty location (5/27 trials), while children who completed Set Size 3 trials first selected an occupied but incorrect location on 11/22 trials and an empty location on 16/22 trials (Fisher's exact test $p = .019$). On Set Size 3 trials, children made errors on 97/204 trials, and the majority of those errors involved selecting an occupied but incorrect location (77/97 trials). Unlike Set Size 2 trials, children's patterns of errors in Set Size 3 trials did not differ as a function of Block Order. Children who completed the Set Size 2 block first selected an occupied but incorrect location on 50/65 error trials, compared with 27/32 for children who completed the Set Size 3 block first (Fisher's exact test $p = .439$). Together with the above results, these data suggest that children may be employing different strategies for Set Size 2 trials depending on whether they completed the more challenging Set Size 3 block first.

Experiments 1 and 2 compared

We next compared children who had observed objects presented and hidden simultaneously (Experiment 1) to children who had observed objects presented and hidden sequentially (Experiment 2). We conducted a repeated measures ANOVA on children's mean proportion correct at each Set Size (2 or 3) with Experiment (Simultaneous or Sequential) and Block Order (Set Size 2 or 3 first) as between subjects factors and Age (in months) as a covariate. We observed no main effect of

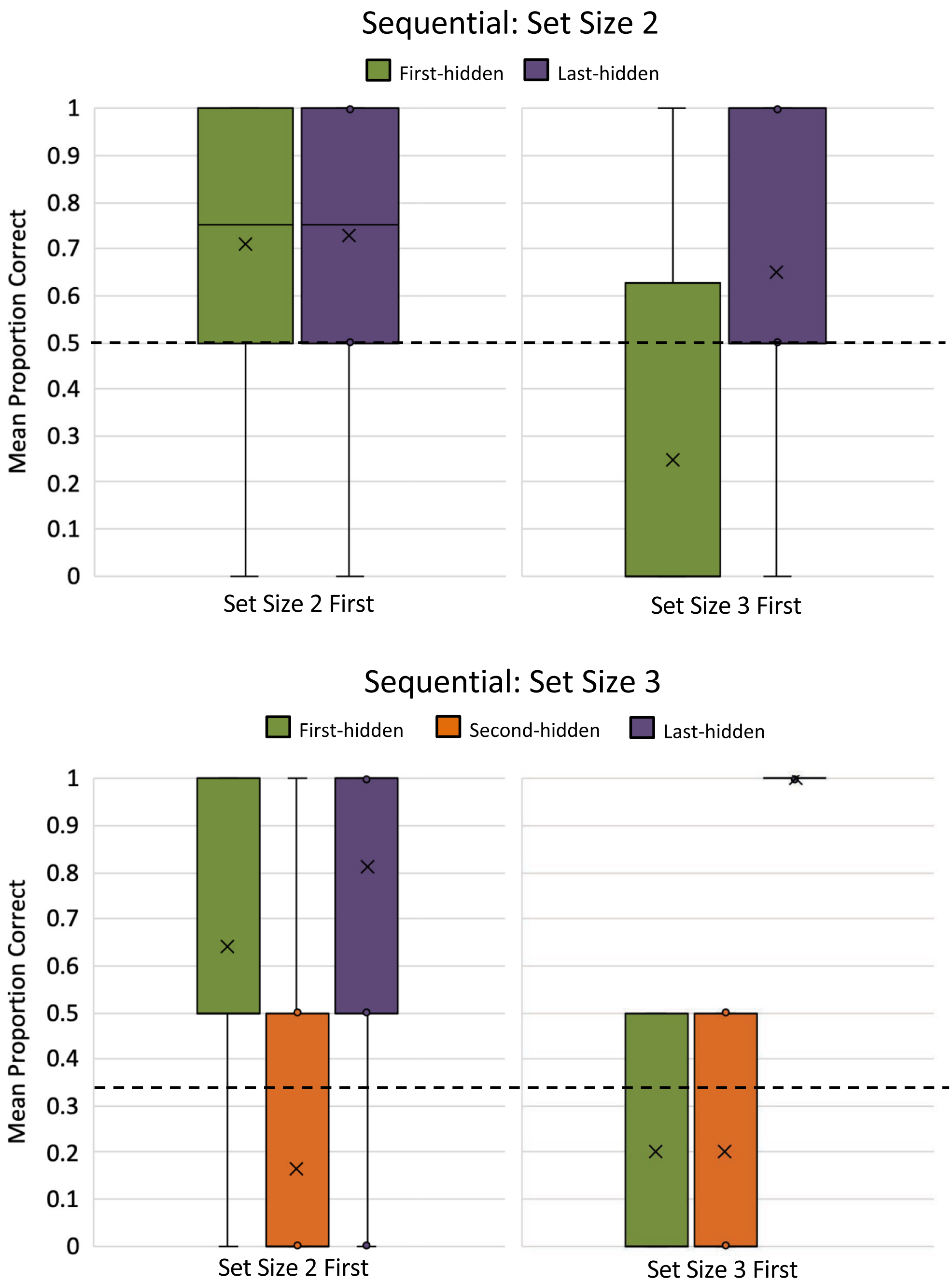

FIGURE 4 Box plots for children's mean proportion correct performance at each serial position as a function of block order (set size 2 block first or set size 3 block first) for set size 2 (top panel) and set size 3 (bottom panel) in Experiment 2.

Set Size ($F[1, 63] = 2.31$, $p = .134$, $\eta_p^2 = .035$) and the Set Size × Experiment interaction also did not reach statistical significance ($F[1, 63] = 3.81$, $p = .055$, $\eta_p^2 = .057$). We observed a significant main effect of Age ($F[1, 63] = 8.59$, $p = .005$, $\eta_p^2 = .120$) and a significant Set Size × Age interaction ($F[1, 63] = 4.21$, $p = .044$, $\eta_p^2 = .063$); children's performance on the task increased across our age range, particularly at Set Size 2. We observed no main effect of Experiment ($F[1, 63] < 1$, $p = .987$, $\eta_p^2 < 1$) or Block Order ($F[1, 63] = 1.09$, $p = .300$, $\eta_p^2 = .017$), but we did observe a significant Experiment × Block Order interaction ($F[1, 63] = 5.12$, $p = .027$, $\eta_p^2 = .075$) and a significant three-way interaction between Set Size, Experiment, and Block Order ($F[1, 63] = 7.58$, $p = .008$, $\eta_p^2 = .107$). Block order had the largest impact on children's performance when objects were hidden sequentially (Experiment 2), particularly on Set Size 2 trials.

We also compared the distributions of children's errors (selecting an incorrect but occupied location, or selecting an empty location) across the two experiments at each Set Size. We observed no significant differences in the frequency of the different types of errors across the two experiments (Set Size 2: Fisher's exact test $p = .199$; Set Size 3: Fisher's exact test $p = .087$).

Discussion

In Experiment 2, we examined toddlers' ability to divide attention between encoding and maintaining in working memory feature-location bound object representations. While we did not observe significant developmental change in children's performance in this task, we did observe an unexpected pattern: both the order of presentation and hiding of the objects and the order in which children completed the set size blocks impacted children's working memory. The implications of these results are discussed in the General Discussion.

GENERAL DISCUSSION

In two experiments, we aimed to characterize working memory for feature-location bound object representations during the toddler years, a period of significant developmental change in the cognitive processes that may support working memory for bound representations. We showed 28- to 40-month-old toddlers sets of two or three different color beads that were presented and hidden in separate locations, either simultaneously (Experiment 1) or sequentially (Experiment 2). We measured children's working memory for the locations of each color bead by showing them a color cue card and asking them to point to the location of that color bead. Thus, children had to encode and maintain integrated representations of "what" and "where" for each object in working memory (Experiment 1) and do so as they divided attention between maintaining representations and encoding additional representations into working memory (Experiment 2).

In Experiment 1, when the entire array was presented and then hidden simultaneously, we found that toddlers could maintain at least three feature-location bound object representations in working memory. When children made errors, the types of errors they made suggested that they were reliably tracking which locations contained objects, but were not necessarily able to maintain bound representations of which object was hidden where. These results are in line with previous work with infants (e.g., Kibbe & Leslie, 2011), and suggest that the format of toddlers' representations of objects in working memory is consistent with an object-file format, in which objects' locations are tracked through 3D space via attentional indexes that can optionally have features bound to them at some attentional cost (Kibbe, 2015; Leslie et al., 1998; Wheeler & Treisman, 2002).

Experiment 1 also revealed an intriguing developmental pattern: toddlers' working memory capacity was characterized by substantial developmental increases for the smaller set size and little developmental change for the larger set size. These results suggest that the attentional resources available to encode and maintain representations in working memory are increasing during toddlerhood, and point to a potential developmental bridge between infancy and childhood with respect to working memory capacity. By the second year of life, infants can maintain in working memory two feature-location bound object representations, but fail to show reliable working memory for three feature-location bound object representations (Cheng et al., 2020; Kibbe & Leslie, 2013). By age 5, children can reliably maintain three to four feature-location bound object representations in working memory (Applin & Kibbe, 2020; Cheng & Kibbe, 2022). Our results show continuity in working memory capacity increases during the intervening developmental time. Our results also highlight the importance of examining developmental change at a finer scale (in our case, by months of age). While toddlers as a group were "above chance" at both set sizes, a finer-grained examination of development in this age group revealed that capacity for two feature-location bound object representations was developing substantially while capacity for three feature-location bound object representations may be just emerging in the toddler period, painting a more nuanced and fuller picture of working memory capacity development.

In Experiment 2, objects were presented and hidden sequentially and toddlers had to *divide* attention between maintaining already-encoded feature-location bound object representations and encoding new representations. We predicted that toddlers' working memory for sequentially presented-and-occluded arrays should vary with the number of objects hidden (similar to infants, Kibbe & Leslie, 2013), reflecting the costs of dividing attention across the to-be-remembered objects and the already-encoded objects in the array. We also predicted that, if the ability to divide attention increases during the toddler period, we would observe developmental increases in performance on the task, potentially interacting with set size, given the results of Experiment 1. Finally, we also might expect the majority of children's errors to be binding errors (e.g., selecting an occupied but incorrect location), similar to Experiment 1.

However, our results were not in line with any of these predictions. In an unanticipated result, we found that the representations that children maintained in working memory varied not by age nor by set size, but by whether children completed the Set Size 2 block first or the Set Size 3 block first. Children who completed the easier Set Size 2 block first reliably remembered two objects across both blocks: they remembered both objects in the two-object array, and the first and last objects in the three-object array. By contrast, children who completed the more challenging Set Size 3 block first appeared to prioritize in working memory the last-hidden object across set sizes. Starting easier resulted in more objects remembered overall. And while most errors were indeed binding errors, children who completed Set Size 3 trials first were more likely to incorrectly choose a location that did not contain an object on subsequent Set Size 2 trials, suggesting that they may not have been tracking the locations of the other objects in the array.

One possibility for this pattern is that children who completed the Set Size 3 block first may have experienced more overall task fatigue. However, we think that possibility is less likely since children seemed to approach the Set Size 3 block using a different strategy from the get-go when those trials are presented first, tracking the last-hidden object only. Another possibility is that children may establish a strategy for doing the task at one set size, and then carry that strategy over to the next set size. For example, children who complete the Set Size 3 block first may have had difficulty tracking all three objects, so may have resorted to a strategy of remembering only the most recent object. They may then have carried that strategy over to subsequent trials where only two objects were hidden, resulting in fewer objects remembered overall, and more irrelevant errors (i.e., selecting an unoccupied location). However, it is not necessarily clear that children who completed the Set Size 2 block first were carrying over their strategy into the Set Size 3 block. Children who completed the Set Size 2 block first successfully remembered two serially adjacent objects in Set Size 2 trials, but then remembered the first- and last-presented and occluded of the three objects in Set Size 3 trials (and not, e.g., the first two or last two objects, analogous to Set Size 2 trials).

Another possibility is that starting easier may result in better overall working memory performance. For example, in a numerical discrimination task, children who were given easier discrimination trials first performed better overall, even at more challenging discriminations, than children who started with the more difficult trials (Odic et al., 2014). Starting with easier trials may have helped children "get their feet under them" as they navigated a cognitively demanding novel task. Interestingly, we did not observe a similar order effect in Experiment 1, which may suggest that children benefitted from completing the Set Size 2 block first *specifically when the task required dividing attention* between representations already stored in working memory and encoding new representations. That is, starting easier may have helped children allocate attention more efficiently as the task became more challenging.

Overall, our results are consistent with the hypothesis that working memory capacity increases with the development of attentional resources available to encode and maintain representations in working memory. However, we also found that toddlers benefit from task structures that can help them allocate attention strategically to better control the contents of working memory and limit interference from information outside of their capacity limits, similar to older children and consistent with the hypothesis that working memory development may be supported by the development of executive functions such as attentional control (e.g., Kane & Engle, 2003). Although we did not observe developmental change during toddlerhood in divided attention abilities, toddlers' performance on the task was qualitatively different than infants' performance, which is primarily limited by the number of objects in the array (Kibbe & Leslie, 2013). Together, our results suggest that both working memory "capacity" (operationalized as the number of feature-location bound representations that can be reliably maintained in working memory) and attentional control (operationalized here as the ability to strategically encode and maintain representations given the demands of the task and the availability of working memory capacity) may both be driving the development of working memory in toddlerhood, with capacity increases perhaps contributing more developmental change than attentional control abilities, at least under the conditions tested here.

Future work would explore the contributions of other potential drivers for increases in working memory capacity in the toddler period. The third year of life is a period of substantial development of expressive vocabulary (Fernald et al., 2006). It is in the toddler period that the ability to verbally recode sets of to-be-remembered objects into "chunks"—with substantial scaffolding—is just beginning to emerge (Kibbe & Feigenson, 2014). Vocabulary size has been linked to the development of phonological working memory in 2-year-olds (Newbury et al., 2015) and 4-year-olds (Gathercole et al., 1999), and in adults, language has been shown to support visual working memory for feature-location bound objects (Forsberg et al., 2019; Overkott & Souza, 2022). Object-based working memory may thus be undergoing substantial qualitative changes during the toddler period. Furthermore, previous work investigating the development of object working memory in infants and toddlers relied on gaze-based measures to examine object representations in infants' and toddlers' working memory (e.g., Cheng et al., 2020; Káldy & Leslie, 2003, 2005; Kibbe & Leslie, 2011, 2013, 2016, 2019). However, the process of *using* information stored in working memory to accomplish behavioral goals (e.g., retrieving a red block) places additional demands on motor coordination and executive functions (Alp, 1994; Diamond, 1998; Diamond et al., 1989; Espy et al., 1999; Marcovitch et al., 2010; Mareschal et al., 1999; McCabe et al., 2010; see also Blankenship & Kibbe, 2019, 2022). In tasks that require an explicit response, toddlers may appear more limited than when responses are implicit (e.g., looking to the location of an object vs. reaching for that object; Ahmed & Ruffman, 1998; Cuevas & Bell, 2010; Morra et al., 2021). Future work would further investigate the contributions of toddlers' developing abilities to developmental change in object working memory capacity between the third and fourth years of life.

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