Developmental Psychology

Development of Updating in Working Memory in 4–7-Year-Old Children

Chen Cheng and Melissa M. Kibbe

Online First Publication, March 21, 2022. http://dx.doi.org/10.1037/dev0001337

CITATION
Cheng, C., & Kibbe, M. M. (2022, March 21). Development of Updating in Working Memory in 4–7-Year-Old Children. *Developmental Psychology*. Advance online publication. http://dx.doi.org/10.1037/dev0001337

Developmental Psychology

© 2022 American Psychological Association
ISSN: 0012-1649

https://doi.org/10.1037/dev0001337

Development of Updating in Working Memory in 4–7-Year-Old Children

Chen Cheng and Melissa M. Kibbe
Department of Psychological and Brain Sciences, Boston University

Children live in a dynamic environment, in which objects continually change locations and move into and out of occlusion. Children must therefore rely on working memory to store information from the environment and to update those stored representations as the environment changes. Previous work suggests that the ability to store information in working memory increases through infancy and childhood. However, less is known about the development of the ability to update stored information. Participants were 63 4–7-year-old children (37 girls; 34 caregivers completed optional demographic forms, and those children were reported as Asian [one], Asian/White [four], Black [one], Middle East/Arab [one], or White [27]; two were Hispanic/Latinx). We asked children to keep track of arrays of hidden items that either remained where they were hidden (static trials) or swapped locations (swap trials) and then to identify from two alternatives which item was hidden in a particular location. We manipulated the number of items in the arrays and the number of times the items swapped locations in order to investigate how increasing storage and updating load impacted children's performance. We found that children's ability to update working memory developed significantly across our age range. Updating appeared to impose a significant one-time cost to working memory performance, regardless of the number of times items swapped. Our results yield new insights into the developmental trajectories of storage and updating in working memory across early childhood.

Keywords: working memory, storage, updating, development

Supplemental materials: https://doi.org/10.1037/dev0001337.supp

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

We live in a dynamic, three-dimensional world. To successfully interact with our environment, we must keep track of objects as they change locations and move into and out of occlusion. This moment-to-moment tracking of objects requires working memory, a fundamental cognitive process that allows us to maintain representations of objects that are no longer in view and to update those representations as the environment changes (Baddeley, 1992; Cowan, 2016; Kibbe, 2015).

There is a growing body of research examining the development of the ability to store information about objects in working memory. This work has shown that the number of object representations that can be stored in working memory increases throughout infancy and childhood (Cowan et al., 2011; Káldy & Leslie, 2005; Kibbe, 2015; Kibbe & Leslie, 2011, 2013; Pailian et al., 2016; Ross-Sheehy et al., 2003; Simmering, 2012), as does the fidelity and precision of those stored representations (Applin & Kibbe, 2020; Burnett Heyes et al., 2012; Cheng et al., 2020; Guillory et al., 2018). The ability to maintain bindings between objects' surface features (e.g., color, shape, texture) and their locations in space is extremely limited in early development, increasing from about one feature-location binding at 6 months (Káldy & Leslie, 2005; Kibbe & Leslie, 2011), to around two feature-location bindings in toddlerhood (Cheng et al., 2019a; Kibbe & Applin, 2022; Kibbe & Leslie, 2013), to around four feature-location bindings at 5–6 years of age (Applin & Kibbe, 2020). Because maintaining feature-bound object representations requires sustained attention (Wheeler & Treisman, 2002), the capacity of working memory to maintain feature-location-bound objects tracks the development of endogenous attention across infancy and childhood (Kibbe & Leslie, 2013).

The ability to update working memory in response to changes in the environment also appears to emerge in infancy. Infants are able to update their representation of the location of one or more occluded objects that moved to new locations out of infants' view (Cheng et al., 2019b; Sophian & Sage, 1983; Wiebe et al., 2010), can update their representations of the contents of containers as new objects are added (Feigenson & Yamaguchi, 2009), and can update their representations of the location or features of an object given verbal input (Ganea & Harris, 2013; Ganea et al., 2007; Özdemir & Ganea, 2020). Infants' updating abilities are extremely limited and fall apart when updating makes significant demands

Chen Cheng https://orcid.org/0000-0001-9419-6945
Melissa M. Kibbe https://orcid.org/0000-0002-9088-2523

This research was supported by National Science Foundation Behavioral and Cognitive Sciences Grant 1844155 awarded to Melissa M. Kibbe. We thank the caregivers and their children who participated in our study and Shiba Esfand and Jiaqi Zhao for their assistance in data collection. This study was not preregistered. Study stimuli and data are available at https://osf.io/9vydc/.

Correspondence concerning this article should be addressed to Chen Cheng, Department of Psychological and Brain Sciences, Boston University, 64 Cummington Mall, Boston, MA 02215, United States. Email: ccheng10@bu.edu

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

on attention, as when infants are required to shift attention between locations (when items are hidden in alternation in two separate locations; Feigenson & Yamaguchi, 2009) or when infants are tasked with updating increasing numbers of feature-location bindings as occluded objects move (Cheng et al., 2019b).

Indeed, maintaining representations of multiple objects as the objects move through space engages different cognitive mechanisms than maintaining representations of objects that stay in one place. While stationary objects' locations can be tracked using a spatial coordinate system, tracking moving objects involves deploying a limited number of "mental pointers" ("fingers of instantiation"; Pylyshyn & Storm, 1988) or "sticky indexes" (Leslie et al., 1998; Pylyshyn, 2000) that can be "attached" to objects in the world. These attentional pointers allow one to track objects without explicitly representing objects' spatial locations from moment to moment. Adults can successfully track around four objects in parallel via object indexes (Pylyshyn & Storm, 1988), and the same mechanisms appear to support multiple object tracking in infancy and childhood (Carey & Xu, 2001; Chen & Leslie, 2012; Leslie et al., 1998; Pylyshyn, 2000), although the number of objects children can track in parallel is more limited than adults and increases across development (Blankenship et al., 2020; O'Hearn et al., 2005, 2010; Trick et al., 2005).

While multiple sticky indexes can be deployed with low attentional cost (Leslie et al., 1998; Pylyshyn, 2000), tracking the specific identities of multiple moving objects imposes significant demands on attention. When asked to report the identities of the tracked objects, adults have demonstrated a "content deficit"—adults tracked the locations of multiple objects but had more difficulty recalling the specific features of those objects, suggesting that bindings between features and objects require serial attention to maintain (Horowitz et al., 2007; Oksama & Hyönä, 2004, 2008). Only a few studies have attempted to examine children's ability to track the identities of multiple moving objects (e.g., Cheng et al., 2019b; Richardson & Kirkham, 2004), and these studies focused on infancy. For example, in one study, 25-month-olds but not 20-month-olds could track the featural identities of two objects that changed locations after becoming occluded (i.e., the occluders behind which the objects were hiding changed locations on the computer screen; Cheng et al., 2019b). This result contrasts with previous work on infants' working memory for objects that do not move after occlusion, in which infants at 9 months of age can maintain representations of two feature-location-bound objects (Káldy & Leslie, 2003; Kibbe & Leslie, 2013).

Together, the above studies suggest that maintaining feature-location bindings in working memory, and updating those representations as objects move through space, may each impose different demands on working memory. However, less is known about how limitations on updating may change—or how maintenance and updating processes may interact—across development. On the one hand, maintenance and updating may operate somewhat independently (Baddeley, 2012; Baddeley & Logie, 1999) and therefore may follow different developmental trajectories. Indeed, previous work suggests that the capacity to store and maintain information in working memory, and the central executive processes that allow manipulation of that information for use in tasks, may develop independently (Gathercole, 1998; Gathercole et al., 2004), and neuroimaging evidence suggests that storage and updating of information in working memory may rely on separate but adjacent brain areas (Postle et al., 1999) that may follow different maturation trajectories (Bunge & Wright, 2007; Crone et al., 2006; Jolles et al., 2011). On the other hand, maintaining and updating representations in working memory both require encoding of incoming information while inhibiting irrelevant information (Conway et al., 2001; Conway & Engle, 1994; Kane & Engle, 2000; Unsworth et al., 2004) and may therefore draw on the same pool of general cognitive resources across development. Further, storing feature-location-bound object representations and updating those representations as the objects move through space or move in and out of occlusion both place significant demands on attention. One therefore might expect a close coupling of maintenance and updating in working memory across development.

A large body of work has explored older children's ability to search, reorganize, or otherwise manipulate the contents of working memory given verbal instructions, but these studies did not require children to update the contents of working memory as the environment changed (Alloway et al., 2006; Bunge & Wright, 2007; Carretti et al., 2005; Crone et al., 2006; ; Federico et al., 2014; Jolles et al., 2011). For example, in *n*-back tasks in which children were presented with serial lists and were asked to respond whether a target item matched an item presented *n* steps back, 10–12-year-old children succeeded in the 1-back task, while performance in a 2-back task increased into adolescence (see Brahmbhatt et al., 2010; Pelegrina et al., 2015; Schleepen & Jonkman, 2010; Vuontela et al., 2003). Federico et al. (2014) asked 6-, 8- and 10-year-olds to recall the serial positions of three images either forward (by retrieving the information stored in working memory) or backward (by reorganizing the stored information) and found accuracy on both tasks increased between the ages of 6 and 10 years, and reaction times decreased significantly between 8 and 10 years of age on the backward task. Linares et al. (2016) tested children's ability to update numerical information stored in working memory by retrieving a stored number and transforming it using an arithmetic operation (e.g., +1) and found performance on this task also increased between late childhood and adolescence.

This work suggests that the ability to modify the contents of working memory undergoes protracted development. However, in these tasks, children are asked to mentally manipulate the contents of working memory top-down (e.g., using a rule or instruction), placing the bulk of the demands of the task on executive functions and prior knowledge. By contrast, previous work with infants examined whether infants could update the contents of working memory in response to observations of environmental change (e.g., an object moving from one location to another). This kind of bottom-up updating of the contents of working memory may rely less on higher-level processes like executive functions and more on lower-level processes like object-based attention and tracking (Blankenship et al., 2020; Flombaum & Scholl, 2006; Flombaum et al., 2010; Jahn et al., 2012; Kibbe & Leslie, 2013; Saiki, 2003; Trick et al., 2006).

Only one study to our knowledge systematically investigated children's ability to update information in working memory in response to dynamic changes in the locations of objects. Pailian et al. (2020) showed 6–8-year-old children sets of colored disks, which were then occluded by inverted cups. The experimenter then moved the cups, swapping the locations of the colored disks several times. Children were then probed to recall the location of a particular color. Thus, to succeed at the task, children needed to

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

repeatedly update their working memory representations of color-location bindings as the occluded colors moved through space. They found that 6–8-year-old children were able to update the locations of the colors when tasked with tracking two hidden colors that swapped locations 1–3 times, but when the number of hidden colors increased to three, their performance declined.

The results of Pailian et al. (2020) suggest that updating the contents of working memory in response to changes in objects' locations may be more costly than simply maintaining that information in working memory. However, there are several gaps in our knowledge. First, the development of working memory updating is unclear. Pailian et al. (2020) compared 6–8-year-old children with adults and with a gray parrot and found that adults and the parrot outperformed children. However, their study was not designed to look at developmental change within their child age range. It remains unknown to what extent storage and updating in working memory follow similar or different developmental trajectories. Second, it is unclear to what extent working memory storage and updating may interact across early childhood. Increasing updating load (e.g., by adding more location changes) may subsequently impact the number of items children can store in working memory. Yet the cognitive cost of updating, and how this cost might change with development, is unknown.

In the current study, we investigated the development of working memory updating in children between the ages of 4 and 7 years. We chose to examine development in children between the ages of 4 and 7 because previous work has shown substantial development in working memory storage in this age range (e.g., Applin & Kibbe, 2020; Cheng & Kibbe, 2022; Pailian et al., 2016; Riggs et al., 2006; Simmering, 2012), making it a period of significant developmental interest with regard to working memory. Specifically, we examined children's ability to update the locations of occluded items as the occluders changed locations, thus requiring children to update in working memory bindings between item and location. Children completed a "hide-and-seek" working memory task, similar to that used by Pailian et al. (2020; see also Pailian & Halberda, 2013). Children first viewed sets of cards depicting illustrations of animals, which were then covered by occluders. In the static block, the objects remained in their original positions. In the swap block, the occluders swapped locations one or more times. To successfully track the objects in the array, children had to store the bindings between objects and their locations in working memory (static block) or update the objects' locations as their occluders moved through space (swap block). We systematically manipulated both the number of objects children had to encode and the number of times the objects swapped locations in order to investigate the effects of increasing storage and updating load on children's performance.

Our task differed from Pailian et al. (2020) in several ways. First, Pailian et al. (2020) asked children to recall the location of a target object. Chance performance therefore varied with the number of locations, making it impossible to directly compare performance across different set sizes. In our task, we asked children to select the identity of an object hidden in a particular location from two alternative choices, equating chance levels across set sizes. This allowed us to directly compare children's performance across set sizes, thereby enabling us to examine how changes in storage and updating load impact performance. Second, Pailian et al. (2020) used physical occlusion (inverted cups) and presented stimuli to children live and in person. Due to the COVID-19 pandemic, we created animated stimuli that could be used to test children online via videoconferencing. Finally, we tested a large sample of children (n = 63) to characterize development between 4 and 7 years of age.

Method

Participants

Sixty-three 4–6-year-old children (M age: 5 years, 7 months; range: 4 years, 1 month to 7 years, 1 month; 37 girls) participated in the study. We predicted a large effect of age and a medium effect of number of times the items swapped places on children's performance, based on previous work (Pailian et al., 2020). A power analysis for multiple linear regression with set size, number of swaps, and age as predictors and participant ID as a random variable suggested a sample size of $N = 59$, assuming a medium effect size, power = 80%, and $\alpha = .05$. All participants were tested individually online using Zoom videoconferencing software. Children completed this study after completing a separate, unrelated study.

Participants were recruited from the greater Boston area through public birth records, family events, and social media ads. Caregivers were given an optional demographics form, and 34 completed the form. Those who completed the form reported their children as Asian (one), Asian/White (four), Black (one), Middle East/Arab (one), and White (27). Two of these participants were identified as Hispanic/Latinx. Thirty-two were from households with at least one parent who had a college degree or higher. Each family received a $10 Amazon gift card for their participation. This study was not preregistered. The study was approved by the Boston University Institutional Review Board under Protocol No. 3594E, "Development of Working Memory in Social & Non-Social Contexts."

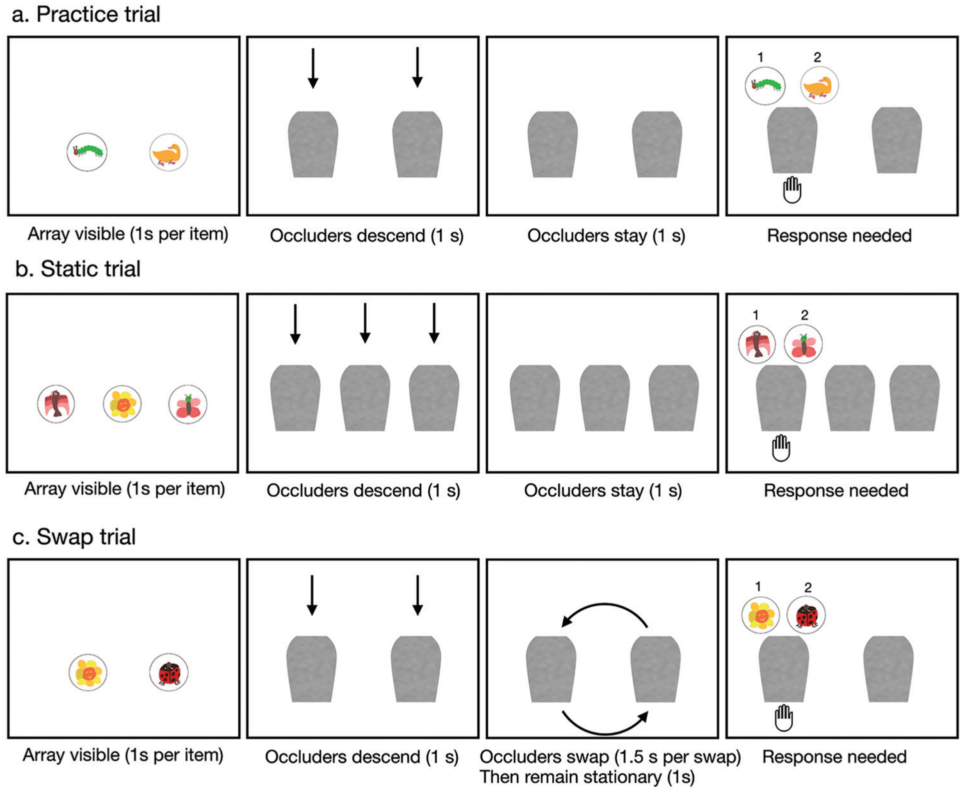
Apparatus and Stimuli

Families were asked to use a device with a screen of at least 10 in. (59 families used a laptop or a desktop computer, and four used an iPad tablet) and to complete the study in a quiet room. The study stimuli were presented in Keynote presentation software by the experimenter using Zoom's screen-sharing function. Stimuli consisted of animated versions of animal characters taken from the World of Eric Carle Mini Memory Match Game (Mudpuppy Toys; see Figure 1).[1] There were 12 distinct animal characters in total. Full stimuli are available at https://osf.io/9vydc/. Sessions were recorded using Zoom's screen recording function and were saved directly to a secure campus server.

[1] Our stimuli were chosen to make the task engaging for young children. Like the stimuli used in Pailian et al. (2020) and other previous work investigating working memory development in children (e.g. Applin & Kibbe, 2020; Pailian et al., 2016; Riggs et al., 2006; Simmering, 2012), the stimuli we used were nameable by children. While stimuli were presented visually and were never named by the experimenter, children could potentially verbally recode the stimuli in order to store the information more efficiently in working memory. However, it is important to note that verbal recoding strategies would be highly inefficient for keeping track of the dynamically changing locations of the objects (e.g., to the left of X, on the outside of Y).

Figure 1

Examples of Practice (Top Panel), Static (Middle Panel), and Swap (Bottom Panel) Trials



Note. On each trial, children were shown sets of items that were then occluded. The occluders either remained stationary (practice and static trials) or swapped locations 1–3 times (swap trials). Children were then asked to identify which of two items was hidden in a particular location. Note that the images depicted in this figure, while similar to the original stimuli, were drawings by one of the authors and were not the original images from the experiment (see "Apparatus and Stimuli" section). See the online article for the color version of this figure.

Design

All children completed a practice trial and two blocks of test trials, a static block and a swap block. The purpose of the static block was to get a baseline measurement of children's storage abilities in the absence of updating. Children were shown sets of three, four, or six cards, which were then occluded, and were asked to identify the card hidden in one of the locations from two alternative choices (the card hidden in the location or another card in the hidden array). Before occluding the cards, the experimenter gave children 1 s per card to encode the array (i.e., 3 s for Set Size 3 trials, 4 s for Set Size 4 trials, 6 s for Set Size 6 trials). We chose these set sizes based on previous work suggesting that 5–6-year-old children can reliably hold the locations of up to four or five objects in working memory (see Applin & Kibbe, 2020) and 4-year-olds can hold around three items in working memory (Simmering, 2012). We therefore expected children in our age range to succeed at Set Size 3, show increasing performance with age at Set Size 4, and show more limited performance at Set Size 6 (since previous work suggested that this set size is likely to be much more challenging for children in our age range). We also predicted that we would be likely to observe developmental change in performance in our age range, particularly for the larger set sizes, consistent with previous work (see, e.g., Applin & Kibbe, 2020).

In the swap block, children were shown sets of two or three items, which then swapped locations 1–3 times, requiring updating in working memory. We chose to limit the number of hidden objects to two or three during swap trials based on the results of Pailian et al. (2020), who found that older children (6–8 years) struggled considerably at Set Size 4 in their updating task, regardless of the number of times the items swapped locations.

Children always completed the static block first, followed by the swap block. In order to prevent task fatigue, children completed trials with smaller set sizes first within each block (see Applin & Kibbe, 2020, and Pailian et al., 2020, for similar approaches). All children completed the study after completing a different study that did not test working memory.

Procedure

Online Setup

The experimenter first greeted the family and guided the parent through the setup procedures for the videoconference (instructing

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

the parent to enter full-screen mode, hide the window that showed the parent and child, and put the experimenter's window at the top center of the screen). The setup procedure ensured that children could see the stimuli and experimenter clearly and would not be able to see themselves during the experiment.

Practice Trial

The experimenter first showed children all the cards on the screen at once and introduced the game as a hide-and-seek game by saying,

> I want to show you all my friends, they are going to play a hide-and-seek game. Each time, some of my friends will show up, then they will hide behind blocks. Your job is to help me find out who is hiding where. First, let's practice.

The experimenter then started the animation for the practice trial, in which two cards, one depicting a caterpillar and one depicting a duck, appeared on the screen. The cards were visible for 2 s, after which the experimenter said, "Now they are going to hide!" The cards were then hidden by two occluders that descended from the top of the screen. After 1 s, an animated hand appeared and pointed to one of the occluders. Two cards appeared above the occluder, one depicting the caterpillar and one depicting the duck, each labeled with a digit (1 or 2; Figure 1, top panel). The experimenter then asked children, "Which one hides here?" After children responded, the experimenter advanced the animation to remove the probed occluder, revealing the hidden card. If the child answered correctly, the experimenter said, "Good job!" and proceeded to the static block. If the child answered incorrectly, the experimenter said, "That's ok, let's try one more time," and repeated the trial. Forty-nine out of 63 children succeeded the first time. The remaining 14 children succeeded the second time.

Static Block

Trials in the static block proceeded similarly to the practice trial. The experimenter said, "Now here come my three friends!" The experimenter then advanced the animation so that three cards with different characters appeared on the screen. These cards were visible for 3 s (1 s per card), after which the experimenter said, "Now they are going to hide!" Three occluders descended from the top of the screen and hid the cards. After 1 s, an animated hand pointed to one of the occluders. Two cards appeared above the occluder, a target card depicting the same character as the card hidden behind the occluder and a distractor card depicting another card in the array. The target and distractor cards were labeled with digits 1 or 2 (Figure 1, middle panel). As in the practice trial, the experimenter prompted children to choose which card was hiding behind the probed occluder by asking, "Which one hides here?" After children responded, the occluder descended to reveal the hidden card. If children chose correctly, the experimenter said, "Good job!" If children answered incorrectly, the experimenter said, "That's fine, let's try another one!" and proceeded to the next trial.

Children completed two Set Size 3 trials, two Set Size 4 trials, and two Set Size 6 trials, presented in a fixed order. The location of the probed card and whether the target card was labeled 1 or 2 were counterbalanced across trials.

Swap Block

To introduce the swap block, the experiment said, "OK, now the game is going to be different. My friends are going to first hide behind the blocks and then they are going to move to different places. Can you help me figure out who is hiding where?" On each trial, children were presented with an array of cards and were given 1 s per card to encode the array. The cards were then hidden simultaneously by a set of occluders that descended from above. On Set Size 2 trials, the two occluders swapped places one, two, or three times. On Set Size 3 trials, children also observed one, two, or three swaps, except that different pairs of occluders swapped locations each time (which occluders swapped was pseudorandomized across trials). Each swap took 1.5 s to complete. Following a 1-s delay, an animated hand appeared pointing to one of the occluders. As in the static block, two cards, a target and a distractor, appeared above the probed location (Figure 1, bottom panel), and the experimenter asked children, "Which one hides here?" The experimenter gave feedback as in the static block. The location of the probed card and whether the target was labeled 1 or 2 were counterbalanced across trials. Children completed two trials of each trial type (see the online supplemental materials for details about which images were displayed on each trial).

The entire task took about 10 min to complete, with children completing two trials per trial type (in the static block: two each of Set Size 3, Set Size 4, and Set Size 6 trials; in the swap block: two each of Set Size 2 one swap, two swaps, three swaps and Set Size 3 one swap, two swaps, three swaps). We chose to limit the number of trials within each trial type to two in order to minimize testing fatigue and attrition in our young sample. Because there were different numbers of trial types within each block, children completed a total of six static trials and 12 swap trials.

Coding

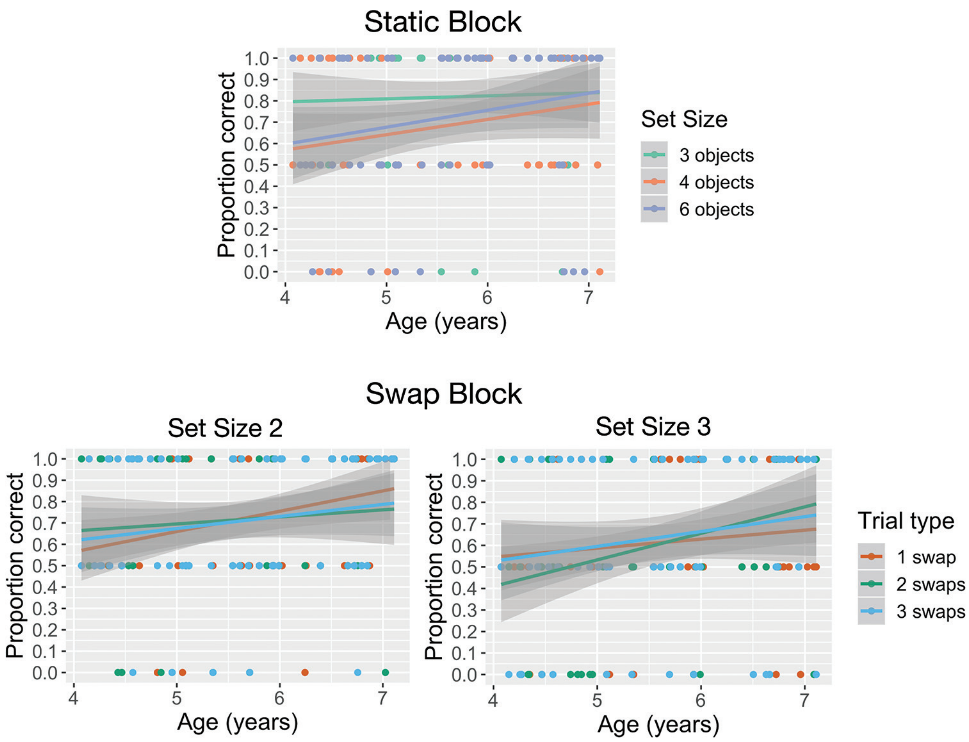
Children's responses were coded as correct or incorrect. For each participant, we computed proportion correct responses for each set size in the static block and for each set size at each number of swaps in the swap block. Data are available at https://osf.io/9vydc/.

Results

Static Block

We first examined children's performance in the static block using a linear mixed-effects model with set size (three, four, or six) and age (continuous, in years) as fixed factors and participant as a random factor. This analysis was conducted in R using the lme4 package (Bates et al., 2014). The best-fitting model did not include the interaction term. We observed a main effect of age, $F(2, 63) = 4.35$, $p = .041$, $\eta_p^2 = .065$, consistent with previous work showing development in working memory capacity between the ages of 4 and 7 (Applin & Kibbe, 2020; Pailian et al., 2016; Simmering, 2012). We observed no main effect of set size, $F(2, 126) = 2.92$, $p = .057$, $\eta_p^2 = .044$; while younger children tended to perform worse at larger set sizes, and performance across set sizes tended to converge with age, these trends were not statistically observed in the final model (see Figure 2, top panel).

Figure 2
Children's Mean Proportion Correct Responses as Function of Age in the Static Block (Top Panel) and in the Swap Block (Bottom Panels)



Note. Dots represent individual children's mean scores. Lines represent linear regression of proportion correct on age for each set size (in the static block) and each trial type (in the swap block). Gray shaded areas represent 95% confidence intervals. See the online article for the color version of this figure.

To examine whether children as a group successfully tracked the identities of the cards in the arrays in the static block, we conducted separate one-sample t tests against chance (.5) at each set size. To correct for three comparisons, we set our alpha criterion for statistical significance to $\alpha = .017$. We also used Bayes factor analysis to quantify the odds of the alternative hypothesis (that children's proportion correct scores are greater than what would be expected by chance) over the null hypothesis (that children's proportion correct scores are not different from chance). These results are summarized in Table 1. While overall performance dropped somewhat between Set Sizes 3 and 4, $t(62) = 2.59$, $p = .012$, children's mean proportion correct responses were significantly above chance at each set size, with Bayes factors offering substantial support for the alternative hypothesis. Inspection of Figure 2, top panel, shows that for the youngest children in our sample, 95% confidence intervals overlapped .5 in the largest set

Table 1
Results From One-Sample t-Test Comparisons to Chance (.5) and Bayes Factor Analyses

Block	Set size	*N* of swaps	Proportion correct *M* (*SD*)	*t*(62)	*p*	*d*	BF_{10}
Static	3	—	.82 (.29)	8.74	<.001*	2.22	>10,000
	4	—	.68 (.35)	4.12	<.001*	1.05	166.67
	6	—	.72 (.36)	4.95	<.001*	1.26	2,551.02
Swap	2	1	.71 (.31)	5.53	<.001*	1.40	>10,000
		2	.71 (.34)	4.94	<.001*	1.25	2,487.56
		3	.71 (.32)	5.13	<.001*	1.30	4,926.11
	3	1	.61 (.33)	2.68	.0095	.68	2.81
		2	.60 (.38)	2.14	.0362	.54	0.87
		3	.63 (.39)	2.72	.0084	.69	3.11

Note. Bayes factors (BF) represent the odds of the alternative hypothesis over the null hypothesis.
* *P* values that fell below our corrected criteria for statistical significance.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

sizes (Set Sizes 4 and 6), suggesting that the ability to successfully encode and retain the identities of the items in the larger arrays may emerge between the ages of 4.5 and 5.

Swap Block

We next examined children's performance in the critical swap block, in which children were asked to update representations stored in working memory. We used a linear mixed-effects model to examine children's proportion correct responses in the swap block with set size (two or three), number of swaps (one, two, or three), and age (continuous, in years) as fixed factors and participant as a random factor. The final best model fit did not include the interaction term.

We observed a main effect of set size, $F(1, 315) = 8.424$, $p = .004$, $\eta_p^2 = .026$, but no main effect of number of swaps, $F(2, 315) = .045$, $p = .955$, $\eta_p^2 < .001$; children performed better on Set Size 2 trials compared with Set Size 3 trials, regardless of the number of times the items in the array swapped locations (see Figure 2). We also observed a main effect of age, $F(1, 63) = 8.828$, $p = .004$, $\eta_p^2 = .12$. Children's performance on the task improved with age across all trial types. Figure 2, bottom panel, shows individual children's proportion correct performance at each set size and for each number of swaps as a function of age.

To examine whether children as a group were able to successfully track the locations of the items in the arrays, we conducted separate one-sample *t* tests against chance (.5) at each set size and for each number of swaps, as well as Bayes factor analysis. To correct for six comparisons, the criterion for statistical significance was set to $\alpha = .008$. These results are summarized in Table 1. Children's mean proportion correct responses were significantly above chance at Set Size 2 at each swap level (one, two, or three swaps), with Bayes factor analysis offering substantial support for the alternative hypothesis that children's performance is reliably above chance. At Set Size 3, children's mean proportion correct responses fell short of our strict criterion for statistical significance, with Bayes factor analysis offering only weak support ($BF_{10} \leq 3$) for the alternative hypothesis at each swap level. Inspection of Figure 2, bottom panel, shows that at Set Size 2, 95% confidence intervals overlapped with chance in our youngest children, but by age 5, children reliably recognized the identity of the item hidden in the probed location, regardless of the number of swaps. At Set Size 3, children's responses did not reliably lie above the chance line until around age 6.

Static and Swap Blocks Compared

To estimate the overall cost of updating on working memory storage, we used Bayes factor analysis to compare mean proportion correct performance at each set size across the static and swap blocks. Unlike traditional null hypothesis significance testing, which gives the probability of the data if it were the case that the null hypothesis is true, Bayes factor analysis yields the probability of a hypothesis given the data. In this case, the null hypothesis is theoretically interesting—if we observe similar performance at different storage and updating loads, it would suggest that these loads are impacting working memory performance in similar ways. We therefore used Bayes factor analysis to compute the odds that the observed data in the two blocks at each set size were drawn from the same distribution, allowing us to quantify the extent to which performance was similar at each set size between the static and swap blocks. Since we observed no main effect of number of swaps and no interactions between set size and number of swaps, we took the mean of children's performance at Set Sizes 2 and 3 in the swap block and compared these grand means to their performance at each set size in the static block.

We found that children's performance at Set Size 2 in the swap block was most similar to their performance at Set Sizes 4 and 6 in the static block, with Bayes factors offering strong support for the null hypothesis (both $BF_{01} > 8$). Odds also favored the null hypothesis in the comparison of children's performance at Set Size 3 in the swap block with both Set Size 4 and 6 in the static block, although Bayes factors were lower, offering only anecdotal support for the null (both $BF_{01} < 5$; see Table S1 for results of all comparisons). Indeed, children's performance was lowest at Set Size 3 swap trials compared with all other trial types (see Figure 3), suggesting that the set sizes we chose for the static block did not yield performance that was strongly comparable to adding updating at Set Size 3.

Overall, this analysis suggests that adding updating to the task imposed a cost to working memory similar to adding at least two items to a to-be-remembered static array. Figure 3 shows mean proportion correct at each set size in both blocks.

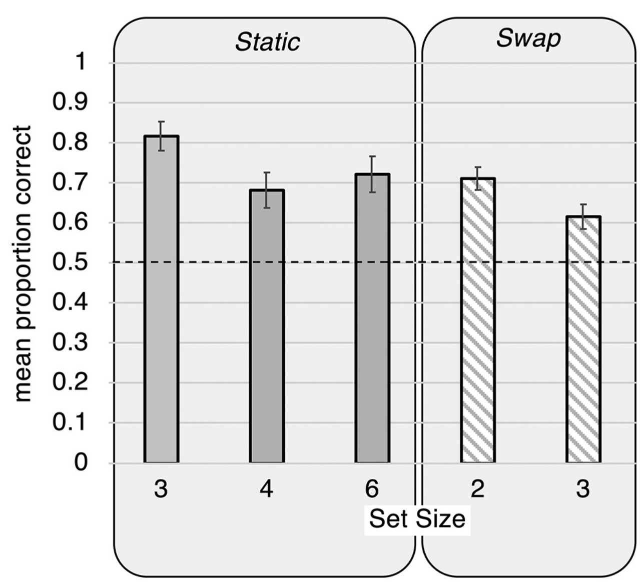
Finally, we asked whether individual children's performance in the static block was correlated with their performance in the swap block, controlling for children's age. We found no correlation between the two blocks, $r(59) = .071$, $p = .582$, suggesting that individual differences in children's working memory capacities were not related to their updating abilities in our age range.

Discussion

We investigated development of the ability to update working memory in response to changes in the locations of items stored in

Figure 3

Mean Proportion Correct Performance in the Static (Gray Bars) and Swap (Striped Bars) Blocks at Each Set Size



Note. Error bars show ± 1 standard error of the mean.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

working memory. We examined children between the ages of 4 and 7 years, a period of significant development in the storage capacity of working memory (e.g., Applin & Kibbe, 2020; Cheng & Kibbe, 2022; Pailian et al., 2016; Simmering, 2012). We found that, when children were asked to store information in working memory without updating (static block), we observed an increase in performance with age consistent with previous work (e.g., Applin & Kibbe, 2020; Pailian et al., 2016; Simmering, 2012). We also found that children's ability to update working memory increased with age, suggesting that working memory updating abilities also are developing substantially between the ages of 4 and 7 years. By around age 5, children could update their working memory representations of the changing locations of arrays of two objects. By around age 6, children could do so for arrays of three objects.

Interestingly, the pattern of results we obtained suggests that updating may impose a significant one-time cost to working memory for 4–7-year-olds, at least under the conditions tested here. When children had to update the locations of objects after they swapped positions one time, performance declined considerably and subsequently remained at that level as more swaps were added. Comparisons between trials in which children had to store items in working memory (static block) and trials in which they also had to update the real-world locations of those stored items (swap block) suggested that the cost of updating may be higher than the cost of storage, and updating may significantly reduce the number of items that are stored in working memory. Previous work by Pailian et al. (2020) found that 6–8-year-olds' ability to update the real-world locations of items stored in working memory declined after one and two location changes and remained at that level for three location changes. While it is not possible to directly compare performance on our task to the results of Pailian et al. (2020) due to differences in response measures, taken together, these results suggest that the load imposed by updating processes may ease with development.

We also found no correlation between children's performance in the static block, in which they were required to maintain representations of stationary objects, and children's performance in the swap block, in which they had to also update information in working memory. This may reflect that the ability to effectively update working memory in response to environmental changes is emerging in this age range. Previous work suggested that working memory storage and updating may engage in different mechanisms (O'Hearn et al., 2005, 2010; Pailian & Alvarez, 2018; Pailian & Halberda, 2013). It is possible that, as children's updating abilities develop, updating capacity and storage capacity may be more closely coupled. Further work is needed to better understand individual differences in storage and updating processes across development.

What might be driving developmental improvement in working memory updating abilities? One possibility is that the cognitive resources that support updating are developing during this period, including the ability to track multiple moving objects via visual attention (Blankenship et al., 2020; Trick et al., 2006) and executive functions like cognitive control (Diamond, 2006; Zelazo et al., 2003), both of which could be playing critical roles in maintaining the feature-location-bound object representations and tracking objects' moving trajectories over time (Spencer et al., 2012). Development of updating abilities may therefore emerge from the development of these support processes. Another, nonmutually exclusive possibility is that younger children may be more susceptible to proactive interference than older children (Kail, 2002; Simmering, 2012) such that the development of inhibitory control would be critical for success in the task (Durston et al., 2002; Williams et al., 1999). In our task, objects swapped locations with each other, requiring children to replace the old information about which object was stored at each location with new information. Thus, children had to suppress previous representations of the contents at each location in order to respond correctly. Indeed, the ability to effectively cope with proactive interference is thought to be a significant source of developmental change in working memory capacity across childhood (Hamilton et al., 2022). Children's ability to update the feature-location pairings in working memory may be less limited if, for example, objects moved to new locations where no previous representation need be inhibited. Future work would examine this possibility.

In our task, we used a two-alternative forced-choice response measure in order to equate chance levels across set sizes, thereby allowing us to directly examine the impact of set size and number of swaps on children's responses. Children were probed to choose the identity of an item in a location, selected pseudorandomly, from two alternative choices: the correct identity or another identity that also appeared on that trial. Thus, children could succeed by correctly remembering the probed location's identity or by correctly remembering the location of the other, distractor identity, ruling that out as a possibility, and selecting the correct response by exclusion. While recent research suggests that the ability to use this kind of exclusive reasoning to solve a working memory task is not reliable until around age 6 (Cheng & Kibbe, 2022), it is nevertheless important to consider the possibility that children's updating abilities could be even more limited in a context in which reasoning by exclusion was not possible. Further work is needed to examine this possibility.

Due to the outbreak of the COVID-19 pandemic, the current study was conducted online; therefore, we have to acknowledge that the findings of the study may reflect the development of working memory updating under the conditions of online testing. Though the testing environments in the laboratory and online are different, a recent study examining children's working memory development using a change-detection paradigm in 4–10-year-olds found a similar developmental trajectory in online testing as observed in laboratory data collection (Ross-Sheehy et al., 2021), providing promising evidence on the comparability of these two data collection environments. Although our study was conducted online, the setup of the online procedures shared many similarities with laboratory data collection, including synchronous, face-to-face interaction between experimenter and child throughout the experiment, experimenter-controlled presentation of stimuli, and a low-distraction environment. Nevertheless, children in our study viewed object movement in only two dimensions (on a screen), and it is possible that children's performance may look different under circumstances closer to those used by Pailian et al. (2020) in which objects were hidden in physical locations and could be physically manipulated by a hand (see Kibbe, 2015, for further discussion). Future work may compare the impact of different testing environments and the role of physical object affordances on children's performance.

In this study, we investigated the process of updating object-location bindings as objects moved through space and changed locations, a highly attentionally demanding form of updating (Kibbe & Leslie, 2013; Saiki, 2003). More work is needed to characterize the developmental trajectories of other types of working memory updating in response to environmental changes across this age range, including feature updating or updating the contents of a location following sequential occlusions. Future work will focus on understanding the cognitive demands of different types of updating processes to yield a clearer picture of the development of working memory updating in early childhood.

References

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, *77*(6), 1698–1716. https://doi.org/10.1111/j.1467-8624.2006.00968.x

Applin, J. B., & Kibbe, M. M. (2020). Young children monitor the fidelity of visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *47*(5), 808–819. https://doi.org/10.1037/xlm0000971

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556–559. https://doi.org/10.1126/science.1736359

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, *63*, 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge University Press. https://doi.org/10.1017/CBO9781139174909.005

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Blankenship, T. L., Strong, R. W., & Kibbe, M. M. (2020). Development of multiple object tracking via multifocal attention. *Developmental Psychology*, *56*(9), 1684–1695. https://doi.org/10.1037/dev0001064

Brahmbhatt, S. B., White, D. A., & Barch, D. M. (2010). Developmental differences in sustained and transient activity underlying working memory. *Brain Research*, *1354*, 140–151. https://doi.org/10.1016/j.brainres.2010.07.055

Bunge, S. A., & Wright, S. B. (2007). Neurodevelopmental changes in working memory and cognitive control. *Current Opinion in Neurobiology*, *17*(2), 243–250. https://doi.org/10.1016/j.conb.2007.02.005

Burnett Heyes, S., Zokaei, N., van der Staaij, I., Bays, P. M., & Husain, M. (2012). Development of visual working memory precision in childhood. *Developmental Science*, *15*(4), 528–539. https://doi.org/10.1111/j.1467-7687.2012.01148.x

Carey, S., & Xu, F. (2001). Infants' knowledge of objects: Beyond object files and object tracking. *Cognition*, *80*(1-2), 179–213. https://doi.org/10.1016/S0010-0277(00)00154-2

Carretti, B., Cornoldi, C., De Beni, R., & Romanò, M. (2005). Updating in working memory: A comparison of good and poor comprehenders. *Journal of Experimental Child Psychology*, *91*(1), 45–66. https://doi.org/10.1016/j.jecp.2005.01.005

Chen, M. L., & Leslie, A. M. (2012). Multiple object tracking in infants: Four (or so) ways of being discrete. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 85–106). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199216895.003.0004

Cheng, C., Káldy, Z., & Blaser, E. (2019a). Focused attention predicts visual working memory performance in 13-month-old infants: A pupillometric study. *Developmental Cognitive Neuroscience*, *36*, Article 100616. https://doi.org/10.1016/j.dcn.2019.100616

Cheng, C., Káldy, Z., & Blaser, E. (2019b). Two-year-olds succeed at MIT: Multiple identity tracking in 20- and 25-month-old infants. *Journal of Experimental Child Psychology*, *187*, Article 104649. https://doi.org/10.1016/j.jecp.2019.06.002

Cheng, C., Káldy, Z., & Blaser, E. (2020). Coding of featural information in visual working memory in 2.5-year-old toddlers. *Cognitive Development*, *55*, Article 100892. https://doi.org/10.1016/j.cogdev.2020.100892

Cheng, C., & Kibbe, M. M. (2022).*Children's use of reasoning by exclusion to track identities of occluded objects* [Manuscript under review]. Department of Psychological and Behavioral Sciences, Boston University.

Conway, A. R., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review*, *8*(2), 331–335. https://doi.org/10.3758/BF03196169

Conway, A. R., & Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. *Journal of Experimental Psychology: General*, *123*(4), 354–373. https://doi.org/10.1037/0096-3445.123.4.354

Cowan, N. (2016). *Working memory capacity: Classic edition*. Psychology Press. https://doi.org/10.4324/9781315625560

Cowan, N., AuBuchon, A. M., Gilchrist, A. L., Ricker, T. J., & Saults, J. S. (2011). Age differences in visual working memory capacity: Not based on encoding limitations. *Developmental Science*, *14*(5), 1066–1074. https://doi.org/10.1111/j.1467-7687.2011.01060.x

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(24), 9315–9320. https://doi.org/10.1073/pnas.0510088103

Diamond, A. (2006). The early development of executive functions. *Lifespan Cognition: Mechanisms of Change*, *210*, 70–95. https://doi.org/10.1093/acprof:oso/9780195169539.003.0006

Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5*(4), F9–F16. https://doi.org/10.1111/1467-7687.00235

Federico, F., Delogu, F., & Raffone, A. (2014). Maintenance and manipulation of object sequences in working memory: A lifespan study. *Neurological Sciences*, *35*(12), 1883–1887. https://doi.org/10.1007/s10072-014-1851-0

Feigenson, L., & Yamaguchi, M. (2009). Limits on infants' ability to dynamically update object representations. *Infancy*, *14*(2), 244–262. https://doi.org/10.1080/15250000802707096

Flombaum, J. I., & Scholl, B. J. (2006). A temporal same-object advantage in the tunnel effect: Facilitated change detection for persisting objects. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 840–853. https://doi.org/10.1037/0096-1523.32.4.840

Flombaum, J. I., Scholl, B. J., & Pylyshyn, Z. W. (2010). Attentional highbeams in tracking through occlusion. *Journal of Vision*, *6*(6), Article 765. https://doi.org/10.1167/6.6.765

Ganea, P. A., & Harris, P. L. (2013). Early limits on the verbal updating of an object's location. *Journal of Experimental Child Psychology*, *114*(1), 89–101. https://doi.org/10.1016/j.jecp.2012.04.013

Ganea, P. A., Shutts, K., Spelke, E. S., & DeLoache, J. S. (2007). Thinking of things unseen: Infants' use of language to update mental representations. *Psychological Science*, *18*(8), 734–739. https://doi.org/10.1111/j.1467-9280.2007.01968.x

Gathercole, S. E. (1998). The development of memory. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *39*(1), 3–27. https://doi.org/10.1111/1469-7610.00301

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, *40*(2), 177–190. https://doi.org/10.1037/0012-1649.40.2.177

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Guillory, S. B., Gliga, T., & Káldy, Z. (2018). Quantifying attentional effects on the fidelity and biases of visual working memory in young children. *Journal of Experimental Child Psychology*, *167*, 146–161. https://doi.org/10.1016/j.jecp.2017.10.005

Hamilton, M., Ross, A., Blaser, E., & Kaldy, Z. (2022). Proactive interference and working memory development. *Wiley Interdisciplinary Reviews – Cognitive Science*. Advance online publication. https://doi.org/10.31234/osf.io/a6yzs

Horowitz, T. S., Klieger, S. B., Fencsik, D. E., Yang, K. K., Alvarez, G. A., & Wolfe, J. M. (2007). Tracking unique objects. *Perception & Psychophysics*, *69*(2), 172–184. https://doi.org/10.3758/BF03193740

Jahn, G., Wendt, J., Lotze, M., Papenmeier, F., & Huff, M. (2012). Brain activation during spatial updating and attentive tracking of moving targets. *Brain and Cognition*, *78*(2), 105–113. https://doi.org/10.1016/j.bandc.2011.12.001

Jolles, D. D., Kleibeuker, S. W., Rombouts, S. A., & Crone, E. A. (2011). Developmental differences in prefrontal activation during working memory maintenance and manipulation for different memory loads. *Developmental Science*, *14*(4), 713–724. https://doi.org/10.1111/j.1467-7687.2010.01016.x

Kail, R. (2002). Developmental change in proactive interference. *Child Development*, *73*(6), 1703–1714. https://doi.org/10.1111/1467-8624.00500

Káldy, Z., & Leslie, A. M. (2003). Identification of objects in 9-month-old infants: Integrating 'what' and 'where' information. *Developmental Science*, *6*(3), 360–373. https://doi.org/10.1111/1467-7687.00290

Káldy, Z., & Leslie, A. M. (2005). A memory span of one? Object identification in 6.5-month-old infants. *Cognition*, *97*(2), 153–177. https://doi.org/10.1016/j.cognition.2004.09.009

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(2), 336–358. https://doi.org/10.1037/0278-7393.26.2.336

Kibbe, M. M. (2015). Varieties of visual working memory representation in infancy and beyond. *Current Directions in Psychological Science*, *24*(6), 433–439. https://doi.org/10.1177/0963721415605831

Kibbe, M. M., & Applin, J. B. (2022). *Tracking what went where across toddlerhood: Feature-location binding in 2-3-year-olds' working memory* [Manuscript under review]. Department of Psychological and Brain Sciences, Boston University.

Kibbe, M. M., & Leslie, A. M. (2011). What do infants remember when they forget? Location and identity in 6-month-olds' memory for objects. *Psychological Science*, *22*(12), 1500–1505. https://doi.org/10.1177/0956797611420165

Kibbe, M. M., & Leslie, A. M. (2013). What's the object of object working memory in infancy? Unraveling 'what' and 'how many.' *Cognitive Psychology*, *66*(4), 380–404. https://doi.org/10.1016/j.cogpsych.2013.05.001

Leslie, A. M., Xu, F., Tremoulet, P. D., & Scholl, B. J. (1998). Indexing and the object concept: Developing 'what' and 'where' systems. *Trends in Cognitive Sciences*, *2*(1), 10–18. https://doi.org/10.1016/S1364-6613(97)01113-3

Linares, R., Bajo, M. T., & Pelegrina, S. (2016). Age-related differences in working memory updating components. *Journal of Experimental Child Psychology*, *147*, 39–52. https://doi.org/10.1016/j.jecp.2016.02.009

O'Hearn, K., Hoffman, J. E., & Landau, B. (2010). Developmental profiles for multiple object tracking and spatial memory: Typically developing preschoolers and people with Williams syndrome. *Developmental Science*, *13*(3), 430–440. https://doi.org/10.1111/j.1467-7687.2009.00893.x

O'Hearn, K., Landau, B., & Hoffman, J. E. (2005). Multiple object tracking in people with Williams syndrome and in normally developing children. *Psychological Science*, *16*(11), 905–912. https://doi.org/10.1111/j.1467-9280.2005.01635.x

Oksama, L., & Hyönä, J. (2004). Is multiple object tracking carried out automatically by an early vision mechanism independent of higher-order cognition? An individual difference approach. *Visual Cognition*, *11*(5), 631–671. https://doi.org/10.1080/13506280344000473

Oksama, L., & Hyönä, J. (2008). Dynamic binding of identity and location information: A serial model of multiple identity tracking. *Cognitive Psychology*, *56*(4), 237–283. https://doi.org/10.1016/j.cogpsych.2007.03.001

Özdemir, B., & Ganea, P. A. (2020). Variability in toddlers' ability to verbally update their mental representations of absent objects. *Journal of Experimental Child Psychology*, *196*, Article 104843. https://doi.org/10.1016/j.jecp.2020.104843

Pailian, H., & Alvarez, G. (2018). Sources of error underlying visual working memory manipulation. *Journal of Vision*, *18*(10), Article 673. https://doi.org/10.1167/18.10.673

Pailian, H., Carey, S. E., Halberda, J., & Pepperberg, I. M. (2020). Age and species comparisons of visual mental manipulation ability as evidence for its development and evolution. *Scientific Reports*, *10*(1), Article 7689. https://doi.org/10.1038/s41598-020-64666-1

Pailian, H., & Halberda, J. (2013). Independent costs for storing and manipulating information in visual working memory. *Visual Cognition*, *21*(6), 704–707. https://doi.org/10.1080/13506285.2013.844966

Pailian, H., Libertus, M. E., Feigenson, L., & Halberda, J. (2016). Visual working memory capacity increases between ages 3 and 8 years, controlling for gains in attention, perception, and executive control. *Attention, Perception & Psychophysics*, *78*(6), 1556–1573. https://doi.org/10.3758/s13414-016-1140-5

Pelegrina, S., Lechuga, M. T., García-Madruga, J. A., Elosúa, M. R., Macizo, P., Carreiras, M., Fuentes, L. J., & Bajo, M. T. (2015). Normative data on the n-back task for children and young adolescents. *Frontiers in Psychology*, *6*, Article 1544. https://doi.org/10.3389/fpsyg.2015.01544

Postle, B. R., Berger, J. S., & D'Esposito, M. (1999). Functional neuroanatomical double dissociation of mnemonic and executive control processes contributing to working memory performance. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(22), 12959–12964. https://doi.org/10.1073/pnas.96.22.12959

Pylyshyn, Z. W. (2000). Situating vision in the world. *Trends in Cognitive Sciences*, *4*(5), 197–207. https://doi.org/10.1016/S1364-6613(00)01477-7

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*(3), 179–197. https://doi.org/10.1163/156856888X00122

Richardson, D. C., & Kirkham, N. Z. (2004). Multimodal events and moving locations: Eye movements of adults and 6-month-olds reveal dynamic spatial indexing. *Journal of Experimental Psychology: General*, *133*(1), 46–62. https://doi.org/10.1037/0096-3445.133.1.46

Riggs, K. J., McTaggart, J., Simpson, A., & Freeman, R. P. (2006). Changes in the capacity of visual working memory in 5- to 10-year-olds. *Journal of Experimental Child Psychology*, *95*(1), 18–26. https://doi.org/10.1016/j.jecp.2006.03.009

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, *74*(6), 1807–1822. https://doi.org/10.1046/j.1467-8624.2003.00639.x

Ross-Sheehy, S., Reynolds, E., & Eschman, B. (2021). Unsupervised online assessment of visual working memory in 4-to 10-year-old children: Array size influences capacity estimates and task performance. *Frontiers in Psychology*, *12*, Article 692228. https://doi.org/10.3389/fpsyg.2021.692228

Saiki, J. (2003). Feature binding in object-file representations of multiple moving items. *Journal of Vision*, *3*(1), 6. https://doi.org/10.1167/3.1.2

Schleepen, T. M., & Jonkman, L. M. (2010). The development of non-spatial working memory capacity during childhood and adolescence and the role of interference control: An N-Back task study. *Developmental Neuropsychology*, *35*(1), 37–56. https://doi.org/10.1080/87565640903325733

Simmering, V. R. (2012). The development of visual working memory capacity during early childhood. *Journal of Experimental Child Psychology*, *111*(4), 695–707. https://doi.org/10.1016/j.jecp.2011.10.007

Sophian, C., & Sage, S. (1983). Developments in infants' search for displaced objects. *Journal of Experimental Child Psychology*, *35*(1), 143–160. https://doi.org/10.1016/0022-0965(83)90075-9

Spencer, J. P., Barich, K., Goldberg, J., & Perone, S. (2012). Behavioral dynamics and neural grounding of a dynamic field theory of multi-object tracking. *Journal of Integrative Neuroscience*, *11*(3), 339–362. https://doi.org/10.1142/S0219635212500227

Trick, L. M., Guindon, J., & Vallis, L. A. (2006). Sequential tapping interferes selectively with multiple-object tracking: Do finger-tapping and tracking share a common resource? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *59*(7), 1188–1195. https://doi.org/10.1080/17470210600673990

Trick, L. M., Jaspers-Fayer, F., & Sethi, N. (2005). Multiple-object tracking in children: The "Catch the Spies" task. *Cognitive Development*, *20*(3), 373–387. https://doi.org/10.1016/j.cogdev.2005.05.009

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(6), 1302–1321. https://doi.org/10.1037/0278-7393.30.6.1302

Vuontela, V., Steenari, M. R., Carlson, S., Koivisto, J., Fjällberg, M., & Aronen, E. T. (2003). Audiospatial and visuospatial working memory in 6-13 year old school children. *Learning & Memory*, *10*(1), 74–81. https://doi.org/10.1101/lm.53503

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48–64. https://doi.org/10.1037/0096-3445.131.1.48

Wiebe, S. A., Lukowski, A. F., & Bauer, P. J. (2010). Sequence imitation and reaching measures of executive control: A longitudinal examination in the second year of life. *Developmental Neuropsychology*, *35*(5), 522–538. https://doi.org/10.1080/87565641.2010.494751

Williams, J. T., Van Eerdewegh, P., Almasy, L., & Blangero, J. (1999). Joint multipoint linkage analysis of multivariate qualitative and quantitative traits. I. Likelihood formulation and simulation results. *American Journal of Human Genetics*, *65*(4), 1134–1147. https://doi.org/10.1086/302570

Zelazo, P. D., Müller, U., Frye, D., Marcovitch, S., Argitis, G., Boseovski, J., Chiang, J. K., Hongwanishkul, D., Schuster, B. V., & Sutherland, A. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, *68*(3), vii–137. https://doi.org/10.1111/j.0037-976X.2003.00269.x

Received December 24, 2020
Revision received November 8, 2021
Accepted December 23, 2021 ■

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.