HHS Public Access

Author manuscript

J Exp Psychol Learn Mem Cogn. Author manuscript; available in PMC 2020 April 01.

Published in final edited form as:

J Exp Psychol Learn Mem Cogn. 2019 April ; 45(4): 700–711. doi:10.1037/xlm0000611.

Statistics learned are statistics forgotten: Children's retention and retrieval of cross-situational word learning

Haley A. Vlach and **Catherine A. DeBrock**

University of Wisconsin, Madison

Abstract

Children are able to resolve the referential ambiguity of learning new words by tracking co-occurrence probabilities across moments in time, a behavior termed cross-situational word learning (CSWL). Although we know that children can use co-occurrence data to map words to objects, the literature has a striking limitation: research has focused on encoding of language and, consequently, children's CSWL has only been assessed at an immediate test. The current research addressed this gap in the literature by examining whether children can retain and retrieve learned words after a retention interval, and whether children's age and individual cognitive abilities contribute to their CSWL performance. The results revealed that children were able to retain and retrieve co-occurrence statistics, but only reliably so at the end of early childhood. Moreover, children's visual recognition memory abilities and the timing of learning events were the two key factors that contributed to children's performance. These findings have implications for theories and computational models of CSWL, and suggest that more research is needed to understand the processes that support CSWL after encoding.

Keywords

word learning; cross-situational learning; statistical learning; language development; memory development; cognitive development

---

In any one moment in time, the world presents children with a vast array of visual and auditory data. To learn new words, children must encode this data and then extract information about relationships between words and referent candidates. Because children must extract word-referent mappings from such a large data set, word learning is characterized as a seemingly impossible task. However, research has shown that children overcome the challenge of the task by tracking co-occurrence data across learning events to determine word-referent mappings. This behavior is termed *statistical word learning* or *cross-situational word learning* (CSWL; Fazly, Alishahi, & Stevenson, 2010; Fitneva & Christiansen, 2011; Kachergis, Yu, & Shiffrin, 2013; Smith, Smith, & Blythe, 2011; Smith & Yu, 2013; Suanda, Mugwanya, & Namy, 2014; Trueswell, Medina, Hafri, & Gleitman, 2013; Vlach & DeBrock, 2017; Vlach & Johnson, 2013; Yurovsky & Frank, 2015).

Correspondence should be addressed to Haley A. Vlach, Department of Educational Psychology, 859 Educational Sciences, 1025 W. Johnson Street, Madison, WI, 53706. hvlach@wisc.edu.
Haley A. Vlach, Department of Educational Psychology, University of Wisconsin, Madison. Catherine A. DeBrock, Department of Educational Psychology, University of Wisconsin, Madison.

One focus of research on CSWL has been to demonstrate children's strong capacity for learning language via co-occurrence data. In particular, this research has shown that this ability comes online early in development and supports multiple aspects of language learning. For instance, studies have shown that children can learn words via CSWL as early as 12 months of age (Smith & Yu, 2008; Escudero, Mulak, & Vlach, 2016), and children can learn multiple types of words using co-occurrence data (e.g., verbs; Scott & Fisher, 2012). Moreover, children can learn phonetic and semantic structure simultaneously by encoding multiple channels of co-occurrence data (minimal phonetic pairs and word mappings; Escudero et al., 2016). This work has led several researchers to argue that children do not need complex tools or linguistic knowledge to learn the meaning of words; instead, children can simply track co-occurrences in the world (for a review, see Yu & Smith, 2012).

A second focus of research has been to elucidate the cognitive abilities that support children's capacity for learning words via CSWL (Scott & Fisher, 2012; Vlach & DeBrock, 2017; Yu & Smith, 2011). This work has shown that several cognitive systems uniquely contribute to the development of CSWL. For instance, Vlach & DeBrock (2017) examined relations between children's CSWL performance and their age, memory (i.e., visual and auditory recognition memory), and language (i.e., receptive vocabulary) abilities. The results revealed that children's age was the least compelling predictor of CSWL performance, and that children's language and memory abilities predicted their performance on the CSWL task above and beyond children's age. Furthermore, visual recognition memory was the strongest predictor of children's CSWL performance, predicting performance above and beyond both age and language abilities. These results suggest that children's ability to track co-occurrence information and determine the meaning of words is minimally influenced by maturation (as measured by children's age). Instead, individual developments across multiple cognitive systems, especially memory systems, are likely supporting the development of CSWL and word learning.

Regardless of the goal of the study, researchers have used a common CSWL paradigm to study children's statistical word learning (Scott & Fisher, 2012; Smith & Yu, 2013; Suanda, Mugwanya, & Namy, 2014; Vlach & DeBrock, 2017; Vlach & Johnson, 2013; Yu & Smith, 2011). In these tasks, children are presented with two novel words (e.g., "fep, wug") and two novel objects in each learning event. Objects are not ostensively named and therefore it is ambiguous as to which word corresponds to each object. However, a single word always co-occurs with one object across learning events; if children track this co-occurrence information, they can successfully determine word-object mappings. Researchers assess children's word learning at a forced-choice test immediately following learning, in which they ask children to map words to referents (e.g., the experimenter will say, "Can you point to the wug?").

Although consistency in the use of this paradigm has led to fruitful comparisons across experiments and a greater understanding of the scope of children's CSWL, there is a striking limitation of the literature: research has only studied children's encoding of language. That is, by administering a test immediately after learning, researchers have learned what children have encoded during learning, but not how they store and later retrieve co-occurrence data in long-term memory. In real-world learning contexts, there are likely to be temporal gaps between learning new words and having to map words to new referents. Thus, to fully understand how CSWL contributes to word learning, we must know if children can retain and retrieve co-occurrence data after learning. The current experiments addressed this limitation of the literature to further understand the scope of children's CSWL.

Current Study

To test whether children are able to retain and retrieve words learned via CSWL, we presented children with a typical CSWL task across two experiments. In particular, we used the task from Vlach & DeBrock (2017) because children in this study had above chance performance at an immediate test. However, in contrast to previous tasks, children experienced a 5-minute delay between learning and testing. This retention interval was chosen because five minutes requires children to access knowledge from long-term memory and it mirrors timescales used in previous studies of children's language development over time (Horst & Samuelson, 2008; Vlach, Sandhofer, & Kornell, 2008). The learning phase of the CSWL task presented half of the object-label pairings on a massed schedule and half of the object-label pairings on an interleaved schedule. Manipulating the presentation timing of the object-label pairings (i.e., massed vs. interleaved schedule) afforded an analysis of how memory demands during learning may affect the ability to retain and retrieve co-occurrence data after a delay. Moreover, the same CSWL task was used in two experiments, which provided a replication of the first experiment and a second test of the competing hypotheses in this work.

Our hypothesis was that children would have weak retention and retrieval of words learned via CSWL. Previous research has shown that infants have significant memory constraints on their CSWL at an immediate test (Vlach & Johnson, 2013) and children rapidly forget newly acquired words (Horst & Samuelson, 2008; Vlach, Ankowski, & Sandhofer, 2012; Vlach, 2014). For example, Vlach and Johnson (2013) presented 16-month-olds with a CSWL task which manipulated the timing of word-object pairings. Half of the word-object pairings were presented in immediate succession (massed schedule) and half of the word-objects pairings were distributed across time (interleaved schedule). The 16-month-old infants were not able to learn the word-object pairings on the interleaved schedule, suggesting that they were not able to retain and retrieve information between the word-object pairing presentations. That is, a brief delay between learning events was a large enough memory demand to cause young infants to fail to learn words during CSWL. We hypothesized that children older than 16 months may also experience memory constraints on their CSWL.

The alternative hypothesis was that children would have strong retention and retrieval of words learned via CSWL. In studies of adults' CSWL, participants are able to retain and retrieve statistics over extended timescales (Vlach & Sandhofer, 2014). For instance, Vlach and Sandhofer (2014) presented adults with a CSWL task with three levels of referential ambiguity during learning: two words and two objects (2 × 2), three words and three objects (3 × 3), and four words and four objects (4 × 4). Half of the participants were tested immediately after learning and half were tested after a one week delay. Results revealed that participants in the 2 × 2 and 3 × 3 learning conditions had above chance performance at the one week delayed test, suggesting that adults are able to retain and retrieve co-occurrence statistics for extended periods of time. Thus, if adults are able to retain and retrieve co-occurrence statistics, children may also be able to retain and retrieve co-occurrence statistics.

Moreover, studies of children's word learning have indicated that, when provided with supportive learning environments, children can retain and retrieve word-object mappings over time (Gordon, McGregor, Waldier, Curran, Gómez, & Samuelson, 2016; Vlach & Sandhofer, 2012; Vlach, Sandhofer, & Bjork, 2014). Fast mapping studies have shown that, although children forget word mappings over time, they can retain and retrieve word-object mappings acquired in ostensive naming environments for months under optimal conditions (Kan, 2014; Vlach & Sandhofer, 2012). In brief, this work suggests that children can retain and retrieve words in supportive learning environments. However, it is unclear if children can retain and retrieve words learned in ambiguous learning environments, in which children must track co-occurrence statistics, to learn word mappings.

We were also interested in whether children's age and cognitive abilities would contribute to children's retention and retrieval of words learned via CSWL. There are many attention, memory, and language processes that could be contributing to the ability to retain and retrieve words. Thus, as a start in this line of research, we focused on specific cognitive abilities that have been studied in prior research on children's encoding of words. In particular, we were interested in whether there would be differences in the cognitive abilities that have been shown to contribute to encoding co-occurrence data (visual and auditory attention, visual recognition memory, and receptive vocabulary; Vlach & DeBrock, 2017) and the cognitive abilities that contribute to the retention and retrieval of co-occurrence data. In Experiment 1, we examined whether children's age was related to their test performance. In Experiment 2, we added three additional tasks to the experiment to measure children's visual-auditory attention, visual recognition memory, and receptive vocabulary. These tasks afforded an analysis of whether and how children's general state of maturation and individual cognitive abilities co-contribute to children's ability to retain and retrieve co-occurrence statistics over time.

EXPERIMENT 1

This study examined whether children are able to successfully retain and retrieve word-object mappings learned via CSWL across time. To test this possibility, we presented children with a CSWL task and tested their word mapping performance after a five minute delay. We hypothesized that children would be able to retain co-occurrence statistics over time, but that performance would be poor due to memory constraints. Moreover, we also predicted that children's ability to retain and retrieve word mappings would improve across early childhood. All procedures were approved by the UW-Madison IRB (Protocol #2015-0826).

Methods

Participants—The participants were 75 preschool-aged children (M_{age} = 39.59 months; range: 25 – 58 months; 36 girls) from predominantly middle to upper SES families in Madison, Wisconsin. Children were recruited from local day care centers and preschools. Children at this point in development were chosen because previous studies have demonstrated that they can successfully retain and retrieve cross-situational statistics at an immediate test (Vlach & DeBrock, 2017). For instance, Vlach & DeBrock (2017; Experiment 2) used the same CSWL task that was used in the current research and found that 2–3 year-olds (61% mean correct responses) and 4–5 year-olds (67% mean correct responses) performed significantly above chance at an immediate test. An additional 4 children participated in the study but were not included in the final sample because of fussiness and inability to follow directions during the experiment (repeatedly choosing object on left side of screen; $N = 1$) or for having performance that was more than 3 SDs above/below the mean ($N = 3$)[1]. Children received a storybook as a thank you for their participation. The sample size was determined by a cutoff of 75 participants successfully completing the study or a 6 month data collection window, whichever cutoff occurred first.

Apparatus & Stimuli—The experiment was administered on a laptop or iPad. As can be seen in Figure 1, visual stimuli for the CSWL task consisted of pictures of novel objects for learning and test trials. Familiar objects were included as attention-getters and were interspersed between learning and test trials. The CSWL task also presented auditory stimuli to children using the laptop or iPad speakers. The timing of transitions between trials was managed by Keynote.

Design and Procedure—All children participated in a CSWL task which consisted of four phases: a (a) training phase, (b) learning phase, (c) retention phase, and (d) testing phase.

Cross-Situational Word Learning (CSWL) Task: The CSWL task was adapted from previous studies of children's CSWL (Vlach & Johnson, 2013) and was the same task used in Vlach & DeBrock (2017), but with a five minute delay between learning and testing.

Training phase: Children began the experiment with a training exercise that familiarized children with the CSWL task (Figure 1). The training phase began with the experimenter prompting children to maintain attention to the presentation by saying, "I'm going to show you some pictures, so please pay attention to the screen." Children were first presented with two successive learning trials. In the first learning trial, two novel objects were shown side by side while children heard two novel words (e.g., "gaz, lep"). In the second learning trial, children again saw two objects, one of which was shown in the first learning trial and a second which was completely novel to the children, and heard two novel words, one of which was presented in the first learning trial and a second which was completely novel to the children (e.g., "lep, kiv"). Novel words were presented for one second each, with a .5 second silence occurring between each word and a .25 second silence at the beginning and end of the trial. The presentation order of words and objects was randomized across trials, such that the first word presented in each trial did not always refer to the leftmost object on the screen and vice versa.

In the training phase, a test trial immediately followed the presentation of the two learning trials. Children were shown two objects and the experimenter asked them to identify referent

[1]Note: Removal of these children from the sample did not affect the overall pattern of results observed.

for the novel word that they learned during both of the two learning trials. For example, on one trial the experimenter asked, “Which one is the lep?” Children’s responses were recorded on paper by the experimenter. Together, the two learning trials and the one test trial comprised one training trial. There were three training trials in total during the training phase.

Learning phase: Immediately following the training phase, the experimenter began the learning phase (Figure 1). Children were presented with 36 learning trials of the same format as those in the training phase. Learning trials were presented to children in immediate succession, with an attention getter trial presented between every three learning trials. Attention getter trials, each consisting of a familiar picture (e.g., a baby) and a familiar nonword sound (e.g., a baby’s giggles), were presented to reorient children’s attention to the screen. Learning trials and attention getter trials lasted for a total of three seconds each, with the learning trials broken down in the same manner as in the training phase.

Children were presented with a total of 12 novel words and 12 novel objects, none of which were used in the training phase. Each novel word always occurred with its corresponding novel object, and the object-label pairings were randomly assigned. The words and objects were presented over six presentation blocks (Figure 1). Each block consisted of six learning trials and presented novel objects on either a massed schedule or an interleaved schedule. Thus, six of the object-label pairings were presented on a massed schedule and six of the object-label pairings were presented on an interleaved schedule. In the massed schedule, word-object pairings were presented in consecutive learning trials. In the interleaved schedule, word-object pairings were presented in the same serial position across those six blocks. All of the novel object-label pairings were presented six times.

Retention phase: During the retention phase, participants participated in five minutes of an unrelated activity. For example, to pass time during the retention interval, the experimenter gave children the opportunity to play with Play-Doh or decorate a paper with stickers.

Testing phase: Once the retention phase ended, the experimenter proceeded to the testing phase (Figure 1). Children were presented with a total of 12 test trials, which tested each object-label pairing presented in the learning phase. For each test trial, children were presented with two novel objects on the screen as the experimenter prompted them to identify the referent for a target novel word. For example, in one test trial the experimenter asked, “Which one is the rin?” and then prompted children to point to their selection. Each test trial was followed by an attention getter trial in order maintain children’s attention to the task. The experimenter recorded children’s responses on paper and proceeded to the next trial until all 12 trials were completed.

Results and Discussion

The central goal of this experiment was to determine whether children can retain and retrieve word mappings learned via CSWL at a delayed test. We first calculated the mean number of correct responses at test ($M = 6.81$ (out of 12), $SD = 1.600$). We then conducted a one-sample t-test against chance performance (6 out of 12), which revealed significantly higher performance than chance, $t(74) = 4.403$, $p < .001$, $d = .51$. Thus, on the group level, children were able to retain and retrieve word mappings at the delayed test.

We were also interested in whether there would be improvements in children's performance across early childhood. To test this possibility, we examined children's age in relation to their CSWL in a manner consistent with previous research; we examined age as a continuous (Vlach & DeBrock, 2017) and discontinuous (Smith & Yu, 2008; Vlach & Johnson, 2013) variable. We first conducted a Pearson's r correlation between children's age (in months) and their number of correct responses at test, which revealed a significant relation, $r(75) = .309$, $p = .007$. A scatterplot and best fit line can be seen in Figure 2. We then divided the sample into quartiles; that is, we divided the sample into four groups by age ($N = 19$ in younger groups, $N = 18$ in oldest group) and calculated the mean number of correct responses at test for each age group, which can be seen in Figure 3. We then conducted an ANOVA with total number of correct responses as the outcome measure, which revealed a main effect of age group, $F(3, 71) = 2.863$, $p = .043$, $\eta_p^2 = .108$. We conducted a series of one-sample t-tests against chance performance which revealed a significantly higher than chance performance in the 47–58 months age group, $t(17) = 5.323$, $p < .001$, $d = 1.25$. In sum, children's performance did improve across early childhood and between 47 to 58 months of age is when children reliably retained words learned via CSWL after a five minute delay.

Finally, we were interested in whether properties of the learning environment, such as the timing of learning events, would affect the degree to which children retained word mappings. Children's performance on the massed and interleaved items by age quartile is presented in Table 1. We started by calculating the number of correct responses on the massed ($M = 3.17$ (out of 6), $SD = 1.132$) and interleaved word-object mappings ($M = 3.64$ (out of 6), $SD = .981$). Next, we calculated a paired-samples t-test comparing performance on the two learning schedules and found that children had significantly higher performance on the interleaved word-object mappings, $t(74) = 2.911$, $p = .005$, $d = .34$. We also conducted one-sample t-tests against chance (3 out of 6) for performance on massed and interleaved items and found that only performance on the interleaved items was significantly above chance, $t(74) = 5.647$, $p < .001$, $d = .65$. Several paired-samples t-tests were conducted to test for primacy or recency effects (e.g., higher performance on first or last items presented during learning), but these tests did not reveal any significant results, ps > .10. Although previous research has shown that interleaved schedules can constrain infants' encoding of CSWL (Vlach & Johnson, 2013), these findings suggest that, after a retention interval, interleaved schedules can promote preschool-aged children's word learning.

This study reveals that both children's developmental state (i.e., age) and properties of the learning environment (i.e., timing of learning) contribute to the degree to which children retain and retrieve word mappings learned via CSWL. Although children were able to retain and retrieve the co-occurrence statistics, children's performance was just above chance, but only reliably so for the older children in the sample. Moreover, children only remembered words on the interleaved schedule. Children as young as 12 months of age can successfully map words to objects via CSWL at an immediate test (Escudero, Mulak, & Vlach, 2016; Smith & Yu, 2008), but this study suggests that not until later in development do children reliably retain and retrieve co-occurrence statistics after a delay. Thus, these findings lead us to our next research question: which cognitive processes contribute to children's poor CSWL performance over time?

To begin answering this question, Experiment 2 examined whether there are individual cognitive abilities that contribute to the ability to retain and retrieve word mappings learned via CSWL. CSWL involves visually attending to referents, pairing referents with auditory labels, remembering these associations, and integrating word mappings into an existing vocabulary. Consequently, there are a plethora of cognitive abilities that may support successful CSWL. To start, we focused our examination on three cognitive systems that have been shown to be related to CSWL during encoding: visual and auditory attention (Yu & Smith, 2011, 2012), recognition memory (Vlach & DeBrock, 2017; Vlach & Johnson, 2013, Vlach & Sandhofer, 2014), and language history (Scott & Fisher, 2012; Smith & Yu, 2013). For instance, Vlach & DeBrock (2017) presented preschool-aged children with a CSWL task and a series of cognitive assessments, such as paired-associates tasks to measure recognition memory and the Peabody Picture Vocabulary Test (PPVT-4th edition) to measure receptive vocabulary. Results showed that there were positive linear relations between children's performance on the immediate test and their memory and language abilities, suggesting that stronger cognitive abilities contributed to stronger encoding of words during CSWL. Moreover, when all cognitive abilities variables were entered into a regression analysis, including children's age, memory abilities were the strongest predictor of performance. In brief, previous research has suggested that all three cognitive abilities uniquely support CSWL above and beyond children's age, but some cognitive abilities may play a larger role than others (i.e., memory abilities may be more supportive of learning than receptive vocabulary).

In line with this work, we predicted that each of these cognitive abilities would support children's encoding of words during the learning phase of CSWL. That is, we hypothesized that these cognitive abilities should also uniquely contribute to children's performance later at the five minute delayed test; stronger encoding often results in stronger retrieval of information across time (Bjork & Bjork, 1992). In particular, we hypothesized that memory abilities would continue to be the strongest predictor of performance, as observed in Vlach & DeBrock (2017), but perhaps to a greater degree at a delayed test, which creates a greater memory demand for children. Indeed, children with stronger memory recognition abilities during learning may be more likely to remember information at a delayed test. If we observed that one and/or multiple of these cognitive abilities contribute to children's CSWL performance at a delayed test, these results would help isolate the mechanisms critical to the development of CSWL. If we did not observe that these cognitive abilities contribute to children's performance, this would suggest that factors other than the individual developmental state of the learner are larger contributors to CSWL performance across time, such as the structure of the learning environment (e.g., timing of word-object co-occurrences).

EXPERIMENT 2

This experiment was designed to replicate Experiment 1 and to examine children's cognitive abilities in relation to their performance on the five minute delayed test. In particular, we examined whether children's visual and auditory attention, recognition memory, and receptive vocabulary contribute to children's CSWL performance. We hypothesized that, because each of these cognitive abilities has been shown to contribute to encoding during the learning phase of CSWL (Vlach & DeBrock, 2017), these cognitive abilities would also support children's retention and retrieval of co-occurrence statistics across time. Moreover, we predicted that these cognitive abilities would predict CSWL performance above and beyond children's age. All procedures were approved by the UW-Madison IRB (Protocol #2015-0826).

Methods

Participants—The participants were 73 preschool-aged children (M_{age} = 40.81 months; range: 26 – 70 months; 36 girls) from predominantly middle to upper SES families in Madison, Wisconsin. Children were recruited from local day care centers and preschools. Children at this point in development were chosen because previous studies have demonstrated that they can successfully retrieve cross-situational statistics at an immediate test (Vlach & DeBrock, 2017). An additional 10 children participated in the study but were not included in the final sample because of fussiness and inability to follow directions during the experiment ($N = 7$) or for having performance on the CSWL task that was more than 3 SDs above/below the mean ($N = 3$)[2]. Children in this experiment did not participate in Experiment 1. Children received a storybook as a thank you for their participation. The sample size was determined by a cutoff of 75 participants successfully completing the study or a 6 month data collection window, whichever cutoff occurred first. A t-test revealed no significant differences in children's age between Experiment 1 and 2, $p > .10$.

Apparatus & Stimuli—The CSWL task was administered on a laptop or iPad. All other tasks were presented with an easel provided with the standardized testing packages.

Design and Procedure—All children participated in four tasks: a CSWL task, the Peabody Picture Vocabulary Test, 4th Edition (PPVT; Dunn & Dunn, 2007), Woodcock-Johnson, 4th Edition, Cognitive Battery Test 13: Visual and Auditory Learning (WJ-VAL; Schrank, McGrew, & Mather, 2014), and the Woodcock-Johnson, 4th Edition, Cognitive Battery Test 14: Picture Recognition (WJ-PR; Schrank et al., 2014). The CSWL task was either presented as the first task or the last task, counterbalanced across participants. A t-test comparing children's performance on the CSWL task when presented first vs. last did not reveal an ordering effect, $p > .10$. The presentation order of the three cognitive tasks (PPVT, WJ-VAL, and WJ-PR) was randomly assigned across participants.

Cross-Situational Word Learning (CSWL) Task: Same as Experiment 1.

[2]Note: Removal of these children from the sample did not affect the overall pattern of results observed.

Peabody Picture Vocabulary Test (PPVT): The Peabody Picture Vocabulary Test, 4th edition (Dunn & Dunn, 2007) is a standardized assessment of receptive vocabulary and was used in this study as a general assessment of children's word learning abilities and vocabulary development. The task was administered according to the PPVT instructions manual (Dunn & Dunn, 2007). In this task, the experimenter presented children with a word (e.g., "sleeping") and children were then asked by the experimenter to point to one of four images that depicted the word (e.g., a drawing of a child sleeping). The experimenter recorded children's answers on a piece of paper and then proceeded to the next training trial until the task was complete.

The PPVT was chosen as the measure of word learning abilities for several reasons. First, language accounts of children's CSWL propose that receptive vocabulary contributes to children's CSWL (Scott & Fisher, 2012; Smith & Yu, 2013) and the PPVT is a standardized test of receptive vocabulary. Second, the PPVT has been widely used as a measure of language abilities in relation to other cognitive abilities (e.g., Miller, Vlach, & Simmering, 2017; Vlach & DeBrock, 2017). Finally, the PPVT task demands are similar to the CSWL task. In both tasks, children are asked to view images and then select via pointing to a single referent/picture at test.

Visual-Auditory Learning (WJ-VAL) Task: This standardized subtest of the Woodcock-Johnson 4th Edition Cognitive Battery is a measure of visual-auditory attention and associative learning (Schrank et al., 2014). Using an easel, the experimenter presented children with short strings of rebuses, pictographic representations of specific words and morphemes. Children were then immediately asked to "read" aloud full-sentence ideas represented by a series of rebuses (e.g., "Bob is in the house"). The experimenter gave corrective feedback to children when they committed errors. This test required children to encode associations between the words and the pictures, and to update their audio-visual lexicon for the rebuses that appeared frequently during the examination. The experimenter ended the test when children hit a preset cutoff number of errors.

Picture Recognition (WJ-PR) Memory Task: This standardized subtest of the Woodcock-Johnson 4th Edition Cognitive Battery measures recognition memory for pictures of objects (Schrank et al., 2014). Children first viewed one or more target objects (e.g., a bowl) on a page of an easel for five seconds and subsequently were shown a second page on the easel containing the target object and one or more distractor objects. The experimenter then asked children to identify the target object from among the distractors. This test required children to encode and retrieve information from their visual memory. To eliminate verbal mediation as a memory strategy, varieties of the same type of object were used as stimuli and distractors (e.g., several different bowls). The test ended when children reached a ceiling of a certain number of errors.

Results and Discussion

The central goals of this experiment were to replicate Experiment 1 and to determine whether the cognitive abilities hypothesized to support and/or constrain CSWL during learning would also contribute to children's retention of word-object co-occurrence statistics across time. We first calculated the mean number of correct responses at test on all tasks. The descriptive statistics and intercorrelations can be seen in Table 2. Scatterplots of each variable in relation to children's CSWL performance can be seen in Figure 4. We then conducted a one-sample t-test against chance performance (6 out of 12) for the CSWL task, which revealed marginally higher performance than chance, $t(72) = 1.818$, $p = .073$, $d = .21$. To determine whether this pattern of performance was significantly different than Experiment 1, we conducted an ANOVA with the total number of correct responses as the outcome measure and experiment as a between-subjects factor. This ANOVA revealed that experiment was a marginally significant factor, $F(1, 146) = 3.186$, $p = .076$, $\eta_p^2 = .021$. These findings suggest that children were able to retrieve word mappings at the delayed test, but to a lesser degree than children in Experiment 1.

We conducted the same age analyses as conducted in Experiment 1 by examining age continuously and discontinuously. We observed a significant relation between children's age and CSWL performance, $r(72) = .256$, $p = .029$, replicating Experiment 1. To further examine the observed relation between age and CSWL performance, we divided the sample into quartiles; that is, we divided the sample into four groups by age ($N = 18$ in younger groups, $N = 19$ in oldest group) and calculated the mean number of correct responses at test for each age group, which can be seen in Figure 3. Although there were differences in the age ranges in the quartiles from Experiment 1, there were no significant differences in the mean age of quartiles across experiments, *p*s > .10. For instance, there was not a significant difference in the youngest quartile in Experiment 1 and the youngest quartile in Experiment 2. We conducted an ANOVA with total number of correct responses as the outcome measure, which revealed a marginal main effect of age group, $F(3, 69) = 2.541$, $p = .063$, $\eta_p^2 = .099$. We conducted a series of one-sample t-tests against chance performance, which revealed significantly higher than chance performance in the 50–70 months age group, $t(18) = 2.455$, $p = .025$, $d = .56$. In sum, children's performance did improve across early childhood and between 50 to 70 months of age is when children reliably retained and retrieved words learned via CSWL after a five minute delay.

As described above, previous research has hypothesized that several cognitive abilities, such as language, attention, and recognition memory abilities, contribute to children's CSWL. To examine whether these same cognitive abilities contribute to children's retention of word-object co-occurrence statistics, we conducted a series of regression analyses. The regression models are presented in Table 3. Collinearity analyses were run for all models using variance inflation factors (VIF); all VIF values were less than 3, suggesting the models do not suffer from issues of collinearity/multicollinearity. The results of these models revealed that children's recognition memory abilities (WJ-PR), but not receptive vocabulary (PPVT) or visual-auditory attention (WJ-VAL), significantly predicted children's CSWL performance above and beyond other factors, including children's age, across all of the models.

Finally, we were interested in whether properties of the learning environment would affect the degree to which children retained word mappings. We started by calculating the number of correct responses on the massed ($M = 3.00$ (out of 6), $SD = 1.344$) and interleaved word-object mappings ($M = 3.48$ (out of 6), $SD = 1.069$). Next, we calculated a paired-samples t-test comparing performance on the two learning schedules and found that children had significantly higher performance on the interleaved word-object mappings, $t(72) = 2.342$, $p = .022$, $d = .27$. We also conducted one-sample t-tests against chance (3 out of 6) for performance on massed and interleaved items and found that only performance on the interleaved items was significantly above chance, $t(72) = 3.833$, $p < .001$, $d = .45$. This finding replicates Experiment 1. Several paired-samples t-tests were conducted to test for primacy or recency effects (e.g., higher performance on first or last items presented during learning), but these tests did not reveal any significant results, *p*s > .10.

Children's performance on the massed and interleaved items by age quartile is presented in Table 1. To determine whether there were differences in performance on the massed and interleaved items by age quartile, we combined each quartile across experiments (i.e., combined age quartile 1 from Exp 1 and age quartile 1 from Exp 2). We then conducted paired-samples t-tests between massed and interleaved item performance within each combined quartile and found that only children in the oldest age quartile demonstrated a significantly higher performance on the interleaved items, $t(37) = 1.995$, $p = .045$, $d = .33$. This finding suggests that interleaved schedules can promote preschool-aged children's CSWL at a delayed test, but only at the point in development at which test performance is reliably above chance.

Taken together, these results suggest that both children's individual cognitive abilities (e.g., recognition memory) and properties of the learning environment (e.g., timing of learning events) contribute to children's CSWL across time. Although children's age, visual and auditory attention abilities, and language abilities were related to their CSWL performance, children's recognition memory was the only factor that uniquely predicted performance above and beyond the other factors. The implications of these findings will be outlined in the General Discussion.

GENERAL DISCUSSION

The central goal of this work was to determine whether children retain and retrieve words learned via CSWL across time. In Experiment 1, children performed significantly above chance on the 5-minute delayed test, suggesting that children can retain and retrieve co-occurrence data. However, children's performance was only marginally above chance in Experiment 2. Younger children did not perform above chance and older children did perform above chance, but older children did not demonstrate impressive performance in either experiment. Taken together, these studies suggest that although children can retain and retrieve words learned during CSWL, children do not possess a strong ability to do so. Indeed, this ability slowly develops across the early childhood period.

We also examined whether individual differences in children's cognitive abilities contributed to their ability to retain and retrieve words learned via CSWL. In particular, we tested whether children's maturational state (as measured by age) and individual cognitive abilities (visual-auditory attention, memory, and language abilities) were related to CSWL performance. The results of Experiment 2 revealed that children's memory abilities were the strongest predictor of performance. Moreover, age no longer predicted children's CSWL performance when children's memory abilities were entered into the regression models.

However, children's visual-auditory attention and receptive vocabulary were not predictive of performance above and beyond children's age. Taken together, these results suggest a central role of memory development, rather than maturation and other cognitive abilities, in children's retention and retrieval of words.

This work yields several theoretical contributions to our understanding of children's CSWL. We highlight three important contributions here: First, rather than expand the scope of children's CSWL like most studies, this study demonstrates limits on children's ability to learn language via CSWL. That is, this work identifies a constraint on children's CSWL; our results suggest that tracking co-occurrence statistics is not enough to support strong retention and retrieval of words over time. Second, these experiments suggest that the degree to which individual abilities contribute to CSWL will vary across timescales. In studies that have examined CSWL during and immediately after learning, several cognitive abilities have been shown to be related to performance (Scott & Fisher, 2012; Vlach & DeBrock, 2017; Yu & Smith, 2011). However, in this work, we observed that visual-auditory attention and language history did not uniquely contribute to CSWL performance after a delay. Instead, memory abilities were the only significant predictor of CSWL performance. This suggests that certain cognitive systems may play large roles in language learning at one point in time, but not across the entire language learning process. Finally, the manner in which co-occurrence statistics are presented to children (i.e., massed vs. interleaved) affects the degree to which words are retained and retrieved over time, and these effects vary across developmental periods. While distributing data across time prevents infants from encoding words learned via CSWL (Vlach & Johnson, 2013), the older children in this study benefitted from an interleaved schedule.

How Do Children Remember Co-occurrence Data?

Although children had poor performance in this task, children do successfully retain and retrieve some words in real-world settings. One hypothesis for the discrepancy between the lab and real-world is that children may need a larger data set, with more repetition across broader timescales, to successfully retain and retrieve words. Repetition serves the dual function of providing (a) more refined statistical probabilities for making mappings and (b) practice retaining and retrieving previously learned information. Indeed, the act of encoding new information also engages learners in the retrieval of prior, related learning (e.g., see study-phase retrieval theories of human memory; Johnston & Uhl, 1976; Thios & D'Agostino, 1976). Moreover, distributing learning events across time promotes long-term memory to a greater degree than presenting learning events in immediate succession (Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Vlach, 2014). In both experiments, children performed above chance on the interleaved schedule, but not massed schedule, suggesting that distributing learning events across time promoted children's memory for words. In brief, children experience a larger data set across broader timescales in real-world learning situations, and this repetition and timing may be critical to providing children with practice retaining and retrieving new words.

Another possibility is that, in real-world settings, specific memory mechanisms are guiding language development, as suggested by the results of Experiment 2. For instance, forgetting is the most ubiquitous process of human memory and inevitably contributes to declining performance over time (for reviews, see Rubin & Wenzel, 1996; Wixted, 2004). Children forget at a more rapid rate than individual in other periods of human development (Brainerd, Reyna, Howe, & Kingma, 1990) and this rapid forgetting could explain why children struggle to retain and retrieve co-occurrence statistics over time. It is important to note that, although forgetting may be constraining children's initial retention and retrieval of words early in language development (e.g., Vlach & Johnson, 2013), forgetting could have beneficial consequences later in development. According to the forgetting-as-abstraction theory (Vlach, 2014; Vlach et al., 2012), children's rapid forgetting causes them to forget irrelevant information at a faster rate than relevant information, accelerating the abstraction process. Indeed, children's rapid forgetting may allow them to forget weak correlations at a rapid rate, supporting the ability to abstract and retrieve co-occurrence information that is useful for word mapping. Future research should examine whether children differentially forget certain types of co-occurrence information (e.g., weak vs. strong correlations) to understand how forgetting can be both constraining and facilitating children's statistical word learning.

A final hypothesis is that the structure of the data set and/or memory processes are not central to the development of children's retention and retrieval of words. Instead, the learning environment is the foundation for supporting children's retrieval of co-occurrence statistics. There is an extensive body of research showing that there are several environmental cues that children use for word learning, from the visual scene that frames a referent (Goldenberg & Sandhofer, 2013; Vlach & Sandhofer, 2011) to the broader social environment (Baldwin & Moses, 2001; Tomasello & Akhtar, 1995). If children were provided with a richer set of cues to retrieve word-object mappings, they may have had stronger performance in the current experiment. For instance, in real-world learning environments, words are introduced in a social context and in a physical space. If these social and physical cues are re-instated during retrieval, as they often are in naturalistic settings, children may be able to successfully retrieve learned words (for a discussion, see Vlach & Sandhofer, 2011).

CSWL is typically characterized by two classes of language development theories: hypothesis testing accounts and associative learning accounts (for reviews, see Yu & Smith, 2012; Yurovsky & Frank, 2015). According to hypothesis testing accounts, children create hypotheses about word-referent mappings, compare the current evidence to the hypotheses, and then select among hypotheses to make inferences about the meaning of words. In contrast, associative learning accounts propose that children encode co-occurrence probabilities that generate a matrix of word–referent associations, which are then used to make determine the meaning of words. We suggest that these models be expanded to incorporate children's changing cognitive abilities as variables that contribute to, and perhaps determine, learning outcomes. For instance, creating a computational model that predicts children's ability to retain and retrieve co-occurrence probabilities as a product of a learning process (e.g., associative matrix and/or hypotheses), environment (e.g., timing of information presented), children's age, visual attention, language, and memory abilities, would be a strong first step in this direction. Indeed, these models may be more accurate in predicting children's ability to retain and retrieve co-occurrence statistics than current models, which often yield strong performance at test and thus do not accurately characterize children's CSWL across time.

In sum, children's ability to retain and retrieve words after a brief delay is fragile; only the oldest children in the sample were able to perform significantly, but not impressively, above chance. This finding suggests that there is a significant developmental lag in the ability to encode words via CSWL (at 12 months of age; Escudero et al., 2016; Smith & Yu, 2008) and the ability to retain and retrieve words learned via CSWL (around four years of age in the current experiments). Future research should examine why children experience such difficulty retaining and retrieving words, and how children overcome the challenge of remembering words after brief and extended delays. In line with the findings of this work, we predict that a collection of individual abilities (e.g., memory abilities) and the learning environment (e.g., the timing at which words are presented to children) will work together to support language development.

Acknowledgments

Many thanks the undergraduate research assistants and lab manager, Matthew Walczak, of the UW-Madison Learning, Cognition, & Development Lab for their help with this project. This work was funded by NIH R03 HD081153-01.

References

Baldwin DA, Moses LJ. 2001; Links between social understanding and early word learning: Challenges to current accounts. Social Development. 10:309–329. DOI: 10.1111/1467-9507.00168

Bjork RA, Bjork EL. 1992; A new theory of disuse and an old theory of stimulus fluctuation. From learning processes to cognitive processes: Essays in honor of William K. Estes. 2:35–67.

Brainerd CJ, Reyna VE, Howe ML, Kingma J. 1990; The development of forgetting and reminiscence. Monographs of the Society for Research in Child Development. 55(3–4)doi: 10.2307/1166106

Bunce JP, Scott RM. 2016; Finding meaning in a noisy world: exploring the effects of referential ambiguity and competition on 2.5-year-olds' cross-situational word learning. Journal of Child Language. :1–27. DOI: 10.1017/S0305000916000180

Cepeda NJ, Pashler H, Vul E, Wixted JT, Rohrer D. 2006; Distributed practice in verbal recall tasks: A review and quantitative synthesis. Psychological Bulletin. 132:354–380. DOI: 10.1037/0033-2909.132.3.354 [PubMed: 16719566]

Diekelmann S, Wilhelm I, Born J. 2009; The whats and whens of sleep-dependent memory consolidation. Sleep Medicine Reviews. 13:309–321. DOI: 10.1016/j.smrv.2008.08.002 [PubMed: 19251443]

Dunn, LM, Dunn, DM. Peabody Picture Vocabulary Test, fourth edition: Manual. Minneapolis, MN: Pearson Assessments; 2007.

Escudero P, Mulak KE, Vlach HA. 2016; Infants encode phonetic detail during cross-situational word learning. Frontiers in Psychology. 7:1419.doi: 10.3389/fpsyg.2016.01419 [PubMed: 27708605]

Fazly A, Alishahi A, Stevenson S. 2010; A probabilistic computational model of cross-situational word learning. Cognitive Science. 34:1017–1063. DOI: 10.1111/j.1551-6709.2010.01104.x [PubMed: 21564243]

Fitneva SA, Christiansen MH. 2011; Looking in the wrong direction correlates with more accurate word learning. Cognitive Science. 35:367–380. DOI: 10.1111/j.1551-6709.2010.01156.x [PubMed: 21429004]

Goldenberg ER, Sandhofer CM. 2013; Same, varied, or both? Contextual support aids young children in generalizing category labels. Journal of Experimental Child Psychology. 115:150–162. DOI: 10.1016/j.jecp.2012.11.011 [PubMed: 23453526]

Gordon KR, McGregor KK, Waldier B, Curran MK, Gómez RL, Samuelson LK. 2016; Preschool children's memory for word forms remains stable over several days, but gradually decreases after 6 months. Frontiers in Psychology. 7:1436.doi: 10.3389/fpsyg.2016.01439 [PubMed: 27713720]

Horst JS, Samuelson LK. 2008; Fast mapping but poor retention in 24-month-old infants. Infancy. 13:128–157. DOI: 10.1080/15250000701795598

Johnston WA, Uhl CN. 1976; The contributions of encoding effort and variability to the spacing effect on free recall. Journal of Experimental Psychology: Human Learning and Memory. 2:153–160. DOI: 10.1037/0278-7393.2.2.153

Kachergis G, Yu C, Shiffrin RM. 2013; Actively learning object names across ambiguous situations. Topics in Cognitive Science. 5:200–213. DOI: 10.1111/tops.12008 [PubMed: 23335580]

Kan PF. 2014; Novel word retention in sequential bilingual children. Journal of Child Language. 41:416–438. DOI: 10.1017/S0305000912000761 [PubMed: 23672812]

Miller HE, Vlach HA, Simmering VR. 2017; Producing spatial words is not enough: Understanding the relation between language and spatial cognition. Child Development. 88:1966–1982. DOI: 10.1111/cdev.12664 [PubMed: 27859021]

Rubin DC, Wenzel AE. 1996; One hundred years of forgetting: A quantitative description of retention. Psychological Review. 103:734–760. DOI: 10.1037/0033-295X.103.4.734

Schrank, FA, McGrew, KS, Mather, N. Woodcock-Johnson IV tests of Cognitive Abilities. Rolling Meadows, IL: Riverside; 2014.

Scott RM, Fisher C. 2012; 2.5-year-olds use cross-situational consistency to learn verbs under referential uncertainty. Cognition. 122:163–180. DOI: 10.1016/j.cognition.2011.10.010 [PubMed: 22104489]

Smith K, Smith ADM, Blythe RA. 2011; Cross-situational learning: An experimental study of word-learning mechanisms. Cognitive Science. 35:480–498. DOI: 10.1111/j.1551-6709.2010.01158.x

Smith LB, Yu C. 2008; Infants rapidly learn word-referent mappings via cross-situational statistics. Cognition. 106:1558–1568. DOI: 10.1016/j.cognition.2007.06.010 [PubMed: 17692305]

Smith LB, Yu C. 2013; Visual attention is not enough: Individual differences in statistical word-referent learning in infants. Language Learning and Development. 9:25–49. DOI: 10.1080/15475441.2012.707104

Suanda SH, Mugwanya N, Namy LL. 2014; Cross-situational statistical word learning in young children. Journal of Experimental Child Psychology. 126:395–411. DOI: 10.1016/j.jecp.2014.06.003 [PubMed: 25015421]

Thios SJ, D'Agostino PR. 1976; Effects of repetition as a function of study-phase retrieval. Journal of Verbal Learning & Verbal Behavior. 15:529–536. DOI: 10.1016/0022-5371(76)90047-5

Tomasello M, Akhtar N. 1995; Two-year-olds use pragmatic cues to differentiate reference to objects and actions. Cognitive Development. 10:201–224. DOI: 10.1016/0885-2014(95)90009-8

Trueswell JC, Medina TN, Hafri A, Gleitman LR. 2013; Propose but verify: Fast mapping meets cross-situational word learning. Cognitive Psychology. 66:126–156. DOI: 10.1016/j.cogpsych.2012.10.001 [PubMed: 23142693]

Vlach HA. 2014; The spacing effect in children's generalization of knowledge: Allowing children time to forget promotes their ability to learn. Child Development Perspectives. 8:163–168. DOI: 10.1111/cdep.12079

Vlach HA, Ankowski AA, Sandhofer CM. 2012; At the same time or apart in time? The role of presentation timing and retrieval dynamics in generalization. Journal of Experimental Psychology: Learning, Memory, & Cognition. 38:246–254. DOI: 10.1037/a0025260

Vlach HA, DeBrock CA. 2017; Remember dax? Relations between children's cross-situational word learning, memory, and language abilities. Journal of Memory and Language. 93:217–230. DOI: 10.1016/j.jml.2016.10.001 [PubMed: 28503024]

Vlach HA, Johnson SP. 2013; Memory constraints on infants' cross-situational statistical learning. Cognition. 127:375–382. DOI: 10.1016/j.cognition.2013.02.015 [PubMed: 23545387]

Vlach HA, Sandhofer CM. 2011; Developmental differences in children's context-dependent word learning. Journal of Experimental Child Psychology. 108:394–401. DOI: 10.1016/j.jecp.2010.09.011 [PubMed: 21074169]

Vlach HA, Sandhofer CM. 2012; Fast mapping across time: Memory mechanisms support children's ability to retain words. Frontiers in Psychology. 3:46.doi: 10.3389/fpsyg.2012.00046 [PubMed: 22375132]

Vlach HA, Sandhofer CM. 2014; Retrieval dynamics and retention in cross-situational statistical learning. Cognitive Science. 38:757–774. DOI: 10.1111/cogs.12092 [PubMed: 24117698]

Vlach HA, Sandhofer CM, Bjork RA. 2014; Equal and expanding learning schedules in children's categorization and generalization. Journal of Experimental Child Psychology. 123:129–137. DOI: 10.1016/j.jecp.2014.01.004 [PubMed: 24613074]

Vlach HA, Sandhofer CM, Kornell N. 2008; The spacing effect in children's memory and category induction. Cognition. 109:163–167. DOI: 10.1016/j.cognition.2008.07.013 [PubMed: 18835602]

Wixted JT. 2004; The psychology and neuroscience of forgetting. Annual Review of Psychology. 55:235–269. DOI: 10.1146/annurev.psych.55.090902.141555

Yu C, Smith LB. 2011; What you learn is what you see: using eye movements to study infant cross-situational word learning. Developmental Science. 14:165–180. DOI: 10.1111/j.1467-7687.2010.00958.x [PubMed: 22213894]

Yu C, Smith LB. 2012; Modeling cross-situational word-referent learning: Prior questions. Psychological Review. 119:21–39. DOI: 10.1037/a0026182 [PubMed: 22229490]

Yurovsky D, Frank MC. 2015; An integrative account of constraints on cross-situational word learning. Cognition. 145:53–62. DOI: 10.1016/j.cognition.2015.07.013 [PubMed: 26302052]

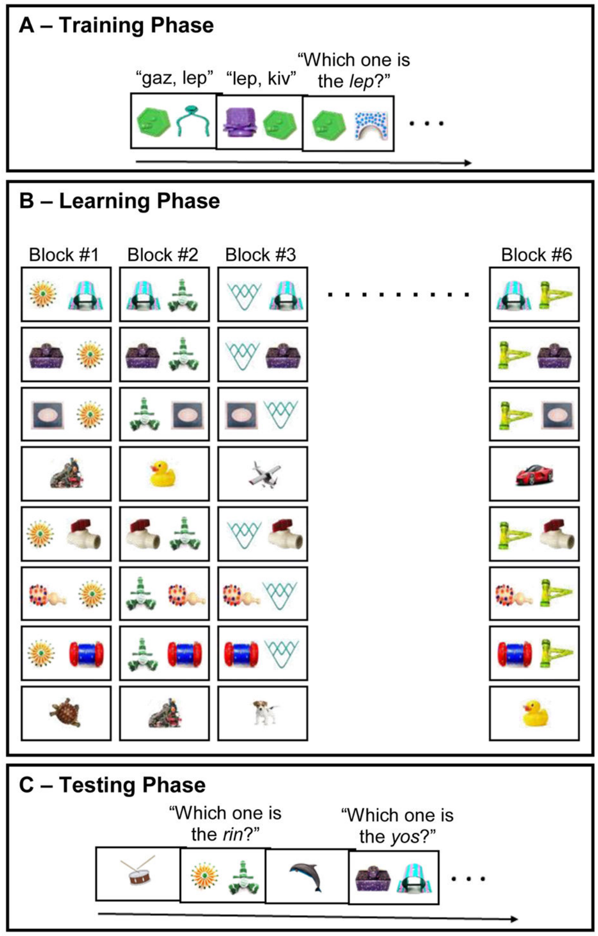

Figure 1.

Examples of stimuli used in the training (Panel A), learning (Panel B), and testing (Panel C) phases of the CSWL task used in Experiment 1 and 2. There was a five minute retention interval between the learning phase and testing phase.

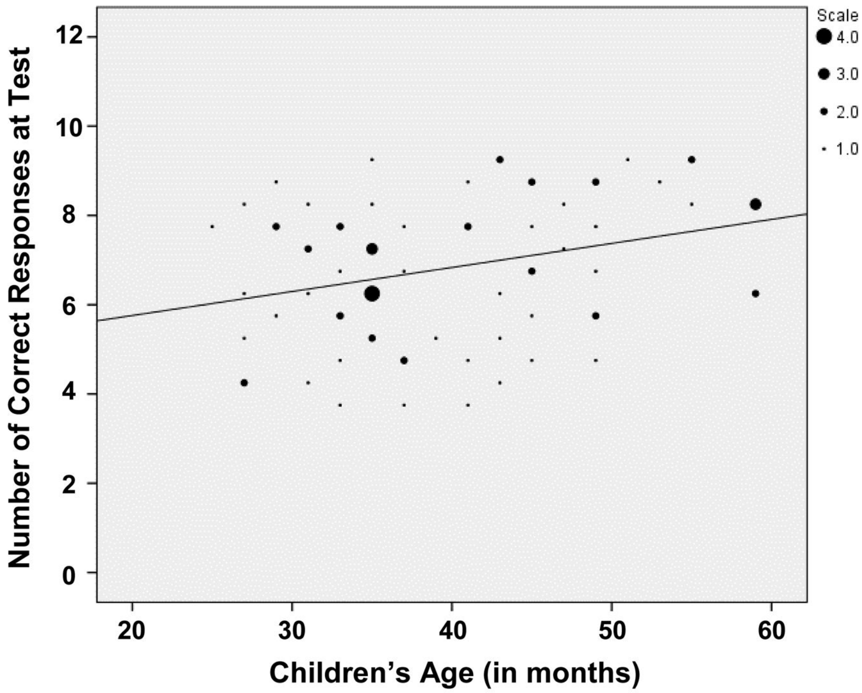

Figure 2.
Scatterplot with best fit line for children's age (in months) in relation to CSWL performance in Experiment 1. Dots are scaled in size; larger dots represent more data points (e.g., 3.0 size = 3 participants).

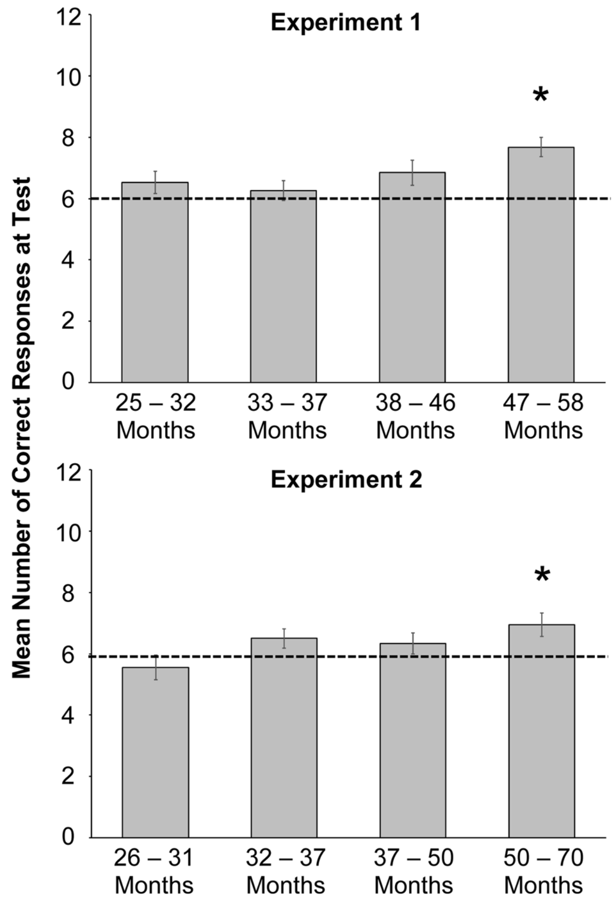

Figure 3.
Mean number of correct responses at test, by age quartile/group, in Experiment 1 and 2. There were no significant differences in mean age in the age quartiles across experiments. Error bars represent one standard error, dashed line represents chance performance, a * indicates group performance that is significantly higher than chance performance, $p < .05$.

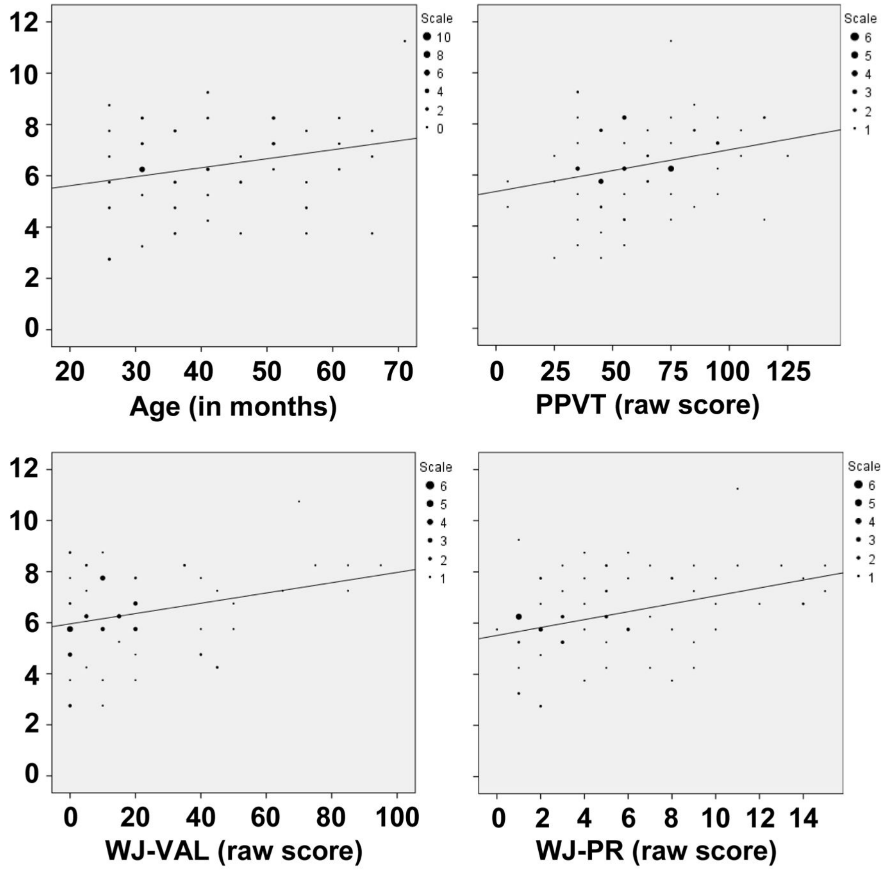

Figure 4.
Scatterplots with best fit lines for children's age (in months), PPVT (raw score), WJ-VAL (raw score), and WJ-PR (raw score) in relation to CSWL performance in Experiment 2. Dots are scaled in size; larger dots represent more data points (e.g., 3.0 size = 3 participants).

Table 1

Descriptive Statistics for Performance on Massed and Interleaved Items in Experiments 1 & 2

	Massed (*M*)	Massed (*SD*)	Interleaved (*M*)	Interleaved (*SD*)
Experiment 1				
Age Quartile 1 (youngest)	3.211	1.084	3.316	0.946
Age Quartile 2	2.895	1.329	3.368	0.831
Age Quartile 3	3.053	1.026	3.786	1.084
Age Quartile 4 (oldest)	3.556	1.042	4.111	0.900
Experiment 2				
Age Quartile 1 (youngest)	2.778	1.556	3.112	0.963
Age Quartile 2	3.000	1.188	3.611	1.243
Age Quartile 3	2.944	1.392	3.500	1.043
Age Quartile 4 (oldest)	3.263	1.284	3.684	1.002

Note. Performance on the massed items and interleaved items was out of 6. Chance performance was 3 out of 6 correct.

Table 2

Descriptive Statistics and Pearson's r Intercorrelations for Variables in Experiment 2

	M	*SD*	Range	1.	2.	3.	4.	5.
1. Age (in months)	40.81	11.76	26 – 70	1				
2. CSWL	6.34	1.61	3 – 11	.256*	1			
3. PPVT	60.40	26.02	4 – 126	.703*	.264*	1		
4. WJ-VAL	19.25	23.00	0 – 97	.705*	.288*	.537*	1	
5. WJ-PR	5.33	4.00	0 – 15	.701*	.385*	.700*	.671*	1

Note. $N = 73$ participants, *indicates $p < .05$. Performance on the CSWL task was out of 12. Data for the PPVT and WJ tests represent raw scores on each test.

Table 3

Hierarchical Regression Analyses for Experiment 2

	R^2	ΔR^2	*B*	*SEb*	*B*
Model 1: Age & Individual Cognitive Abilities					
Step 1:	.066	.066*			
Age (in months)			.035	.016	.256*
Step 2A:	.080	.014			
Age (in months)			.019	.022	.138
PPVT (raw score)			.010	.010	.167
Step 2B:	.089	.023			
Age (in months)			.014	.022	.105
WJ-VAL (raw score)			.015	.011	.214
Step 2C:	.149	.083*			
Age (in months)			−.004	.021	−.028
WJ-PR (raw score)			.162	.062	.405*
Model 2: Age & All Cognitive Abilities					
Step 1:	.066	.066*			
Age (in months)			.035	.016	.256*
Step 2:	.152	.086+			
Age (in months)			−.009	.026	−.069
PPVT (raw score)			.001	.011	.008
WJ-VAL (raw score)			.006	.012	.082
WJ-PR (raw score)			.150	.073	.373*
Model 3: All Cognitive Abilities					
Step 1:	.150	.150*			
PPVT (raw score)			−.001	.010	−.017
WJ-VAL (raw score)			.004	.011	.056
WJ-PR (raw score)			.144	.072	.360*

Note.

Author Manuscript
Author Manuscript
Author Manuscript

* indicates $p < .05$ and + indicates $.05 < p < .10$.

Predictor variable in all models: Performance on CSWL task.