Journal of Memory and Language 93 (2017) 217–230

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Remember dax? Relations between children's cross-situational word learning, memory, and language abilities

Haley A. Vlach *, Catherine A. DeBrock

University of Wisconsin, Madison, United States

ARTICLE INFO

Article history:
Received 4 March 2016
revision received 7 October 2016
Available online 9 November 2016

Keywords:
Word learning
Statistical learning
Language development
Memory development
Cognitive development

ABSTRACT

Learning new words is a difficult task. Children are able to resolve the ambiguity of the task and map words to referents by tracking co-occurrence probabilities across multiple moments in time, a behavior termed cross-situational word learning (CSWL). Although we observe developments in CSWL abilities across childhood, the cognitive processes that drive individual and developmental change have yet to be identified. This research tested a developmental systems account by examining whether multiple cognitive systems co-contribute to children's CSWL. The results of two experiments revealed that multiple cognitive domains, such as memory and language abilities, are likely to drive the development of CSWL above and beyond children's age. The results also revealed that memory abilities are likely to be particularly important above and beyond other cognitive abilities. These findings have implications for theories and computational models of CSWL, which typically do not account for individual children's cognitive capacities or changes in cognitive capacities across time.

Introduction

The world presents children with a seemingly infinite amount of information in just one moment in time. This large amount of information imposes a challenging task when learning language. For each new word that children learn, there are a theoretically infinite number of potential referents for this word. Despite the challenge of the task, children are remarkable word learners; after the first few years of life, children quickly map a word to the correct referent with only a few learning trials (e.g., Carey & Bartlett, 1978).

Research on word learning has historically focused on how children can resolve ambiguity in a single moment in time. However, in real-world language learning environments, children must resolve ambiguity across several moments in time to learn words. Thus, recent research has shifted toward examining whether children resolve ambiguity across multiple learning events. This work has revealed that infants and children can track the co-occurrence of words and objects across learning events and later use this information to infer word-object mappings. This behavior is commonly termed *cross-situational word learning (CSWL)*. Over the last 10 years, there has been significant growth in research on children's CSWL (Scott & Fisher, 2012; Smith & Yu, 2008, 2013; Suanda, Mugwanya, & Namy, 2014; Vlach & Johnson, 2013; Vouloumanos & Werker, 2009; Yu & Smith, 2011) and adult and computational models of children's CSWL (Fazly, Alishahi, & Stevenson, 2010; Fitneva & Christiansen, 2011; Kachergis, Yu, & Shiffrin, 2013; Medina, Snedeker, Trueswell, & Gleitman, 2011; Smith, Smith, & Blythe, 2011; Trueswell, Medina, Hafri, & Gleitman, 2013; Vlach & Sandhofer, 2014; Yu & Smith,

* Corresponding author at: Department of Educational Psychology, 859 Educational Sciences, 1025 W. Johnson Street, Madison, WI 53706, United States.

E-mail address: hvlach@wisc.edu (H.A. Vlach).

http://dx.doi.org/10.1016/j.jml.2016.10.001
0749-596X/

2007, 2012; Yurovsky & Frank, 2015; Yurovsky, Yu, & Smith, 2013).

In a typical CSWL paradigm (e.g., Smith & Yu, 2008; Vlach & Johnson, 2013), children are presented with a series of ambiguous learning trials, each trial consisting of two novel words and two novel objects presented in random order. After learning, children are presented with test trials that consist of two objects presented during learning. Children are then asked to map a word to one of the two objects. The results of these studies have revealed that young infants can successfully infer word-object mappings using CSWL (Smith & Yu, 2008). Moreover, the ability to learn word-object mappings continues to develop across the second year of life (Vlach & Johnson, 2013; Vouloumanos & Werker, 2009) and early childhood years (Scott & Fisher, 2012; Suanda et al., 2014; Woodard, Gleitman, & Trueswell, 2016). A key finding of this research is that there are striking individual differences in the degree to which infants and children can learn words during CSWL (e.g., Scott & Fisher, 2012; Yu & Smith, 2011). Thus, a central pursuit in studying children's CSWL has been to identify the cognitive processes that drive changes and improvements in performance.

One proposal is that changes and improvements in language development are a result of general maturation and maturational constraints (e.g., Newport, 1990). According to this account, language learning abilities improve in efficiency and capacity via maturation of the brain over time. That is, the age of the learner, a proxy measure of maturation, is the largest contributor to language learning outcomes. Thus, the maturation account would predict a strong relation between children's age and CSWL performance. Additionally, the maturation account would predict that other factors (e.g., memory abilities) play a more minor role in driving changes in early word learning.

In contrast, other theoretical accounts propose that a certain cognitive system plays a particularly important role in development, above and beyond age. Cognitive systems are broadly defined as mental systems that share representations and mechanisms (e.g., Smith & Thelen, 2003; Van Geert, 1991), such as visual attention, language, and memory. For instance, one of these proposals is that children's general vocabulary development and word learning abilities drive CSWL. The central tenet of this account is that, as children have gained practice learning words, they learn new words faster and in more challenging learning environments (Scott & Fisher, 2012; Smith & Yu, 2013). Evidence for this proposal comes from studies examining children's vocabulary size in relation to their CSWL performance (Scott & Fisher, 2012); children with larger vocabularies have higher performance on more difficult CSWL tasks than children with smaller vocabularies. In brief, the language account proposes that children's developing language abilities drive changes in children's CSWL.

A final proposal is that changes in children's memory abilities contribute to CSWL (Vlach & Johnson, 2013; Vlach & Sandhofer, 2014). The central tenet of this account is that children must encode, retain, and retrieve a large amount of information during CSWL. That is, tracking and later retrieving co-occurrence information imposes a significant memory demand on young learners. Evidence for this proposal comes from studies demonstrating that placing small memory demands on learners during CSWL can make infants (Vlach & Johnson, 2013) and adults (Vlach & Sandhofer, 2014) fail to successfully retrieve and infer learned words. Thus, according to the memory account, improvements in memory abilities are likely to be the primary cognitive mechanism that drive changes in children's CSWL.

Although various theoretical accounts have emerged, many accounts have yet to be directly tested. For instance, researchers have argued that memory abilities are the primary driver of improvements in children's CSWL (e.g., Vlach & Johnson, 2013), but have yet to demonstrate that children's memory abilities predict their CSWL performance. The hypothesis that memory abilities are important is inferred from changes in learners' performance when memory demands are placed on learners (Vlach & Johnson, 2013; Vlach & Sandhofer, 2014) rather than testing relations between learners' abilities and CSWL performance. Moreover, many studies do not control for age in their examination of individual differences and CSWL performance. As a result, it could be that relations observed between a particular cognitive ability and CSWL (e.g., vocabulary size and CSWL) are a result of children's age, rather than a particular cognitive system. The current work addresses these limitations of previous research on CSWL.

Critically, this work is the first to empirically test a developmental systems theory of CSWL. According to this theoretical framework (for examples of systems theories, see Smith & Thelen, 2003; Van Geert, 1991), changes in CSWL performance are a result of several cognitive systems working together to support learning and development. That is, although one cognitive system may support and/or constrain learning more than other cognitive systems, several cognitive systems must co-contribute to learning for developmental change to occur. Thus, the goal of this work was to determine whether multiple cognitive systems, and many cognitive abilities within one system, contribute to individual and developmental differences in CSWL above and beyond age.

The current research examined relations between children's age, memory abilities, language abilities, and CSWL performance. We examined these relations in a broad age range of children (2–5-year-olds) to capture a wide array of individual differences in age, cognitive abilities, and CSWL performance. In Experiment 1, children were presented with a CSWL task, a general assessment of memory abilities (i.e., paired-associates task), and a general assessment of language abilities (i.e., Peabody Picture Vocabulary Test, 4th edition). In line with the research outlined above, we predicted that both memory and language abilities would predict children's CSWL performance. Moreover, we hypothesized that these cognitive capacities would predict children's CSWL performance above and beyond age. We also examined the relative contributions of age, memory abilities, and language abilities to children's CSWL.

To foreshadow the results of Experiment 1, children's memory abilities were a strong predictor of children's CSWL performance. To further test the developmental systems theory, we examined whether multiple cognitive abilities within a system (i.e., multiple memory abilities) uniquely contribute to individual and developmental differences in CSWL performance. Thus, in Experiment 2, children were presented with a CSWL task and three memory tasks. Each memory task assessed memory abilities that may support CSWL in one moment in time (i.e., in one learning trial). Taken together, these studies afforded an opportunity to understand if one or multiple cognitive capacities drive individual and developmental differences in CSWL.

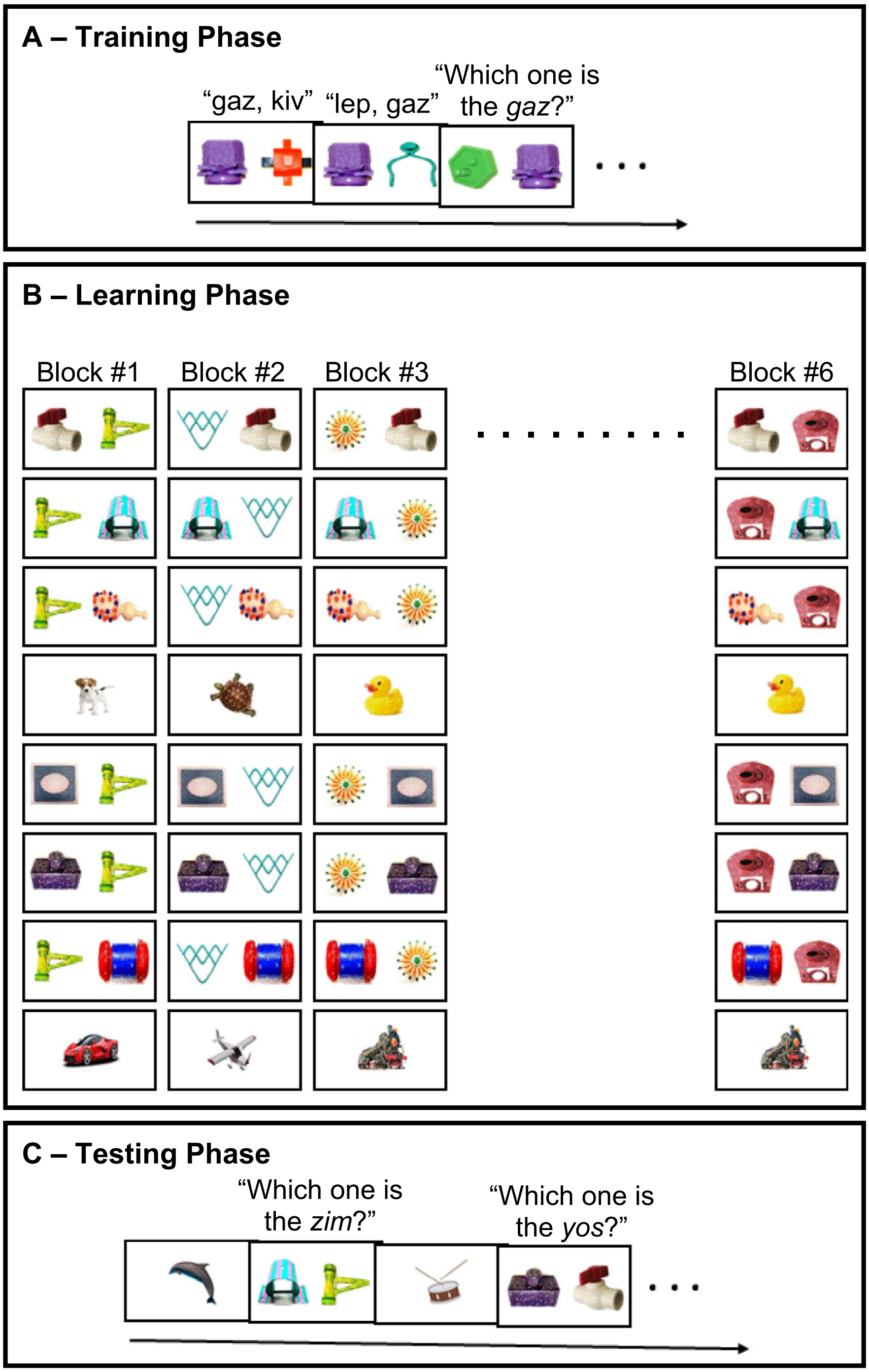

Fig. 1. Examples of stimuli used in the training (Panel A), learning (Panel B), and testing (Panel C) phases of the CSWL task used in Experiment 1 & Experiment 2. All word-object mappings presented in the learning phase were tested in the testing phase.

Experiment 1

This study examined whether there are relations between children's CSWL performance and their age, memory abilities, and language abilities. To test this possibility, children were presented with a CSWL task, a memory task, and a language task. We hypothesized that, above and beyond age, both memory and language abilities would contribute to performance.

Methods

Participants

The participants were 47 preschool-aged children (M_{age} = 47.81 months; range: 22–66 months; 26 girls). Children were recruited from local day care centers and preschools. Children at this point in development were chosen based upon research demonstrating that, after 20 months of age, children are able to learn words using cross-situational statistics across several timescales (Vlach & Johnson, 2013). An additional 19 children participated in the study but were not included in the final sample because of fussiness (e.g., inability to sit still, running away from experimenter, etc.) and/or inability to follow directions during the experiment (e.g., not looking at the screen for more than 30 s, always choosing object on right side of screen at test, etc.). This attrition rate (28%) is lower than or comparable with prior studies on children's CSWL (Vouloumanos & Werker, 2009; Yu & Smith, 2011). Children received a storybook as a thank you for their participation.

Apparatus & stimuli

Most of the experiment was administered on a laptop or iPad. As can be seen in Figs. 1 and 2, visual stimuli consisted of drawings and/or pictures of objects presented on the laptop or iPad screen. Images and pictures were approximately 3.3″ and 2.75″ in size and presented at a resolution of 640 × 480. For learning trials with two images, there was an average 2″ spacing between images. The CSWL task also presented auditory stimuli to children using the laptop or iPad speakers at approximately 75 dB. The presentation timing of the stimuli was controlled by Keynote. The PPVT was administered using the PPVT presentation easel.

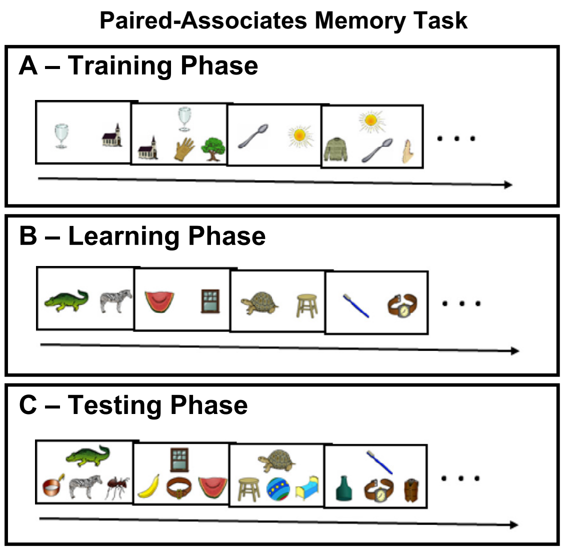

Fig. 2. Examples of stimuli used during the training (Panel A), learning (Panel B), and testing (Panel C) phases of the paired-associates memory task used in Experiment 1. All picture paired-associates presented in the learning phase were tested in the testing phase.

Design

All children participated in three tasks: the Peabody Picture Vocabulary Test, 4th edition (PPVT), a cross-situational word learning (CSWL) task, and a paired-associates memory task.

Procedure

The ordering of the three tasks was randomly assigned for each participant. The experiment began with the first task and ended with the completion of the third task. The duration of the entire experiment was about 30 min.

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., "chair") 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 chair). 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 language 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 used in studies of children's word learning in relation to other cognitive abilities (e.g., Miller, Vlach, & Simmering, in press). Finally, the PPVT task demands are similar to the CSWL task. Children are asked to view images and then select via pointing to a single referent/picture at test in both tasks.

Cross-Situational Word Learning (CSWL) Task. The CSWL task was adapted from Vlach and Johnson (2013) and was designed to be an assessment of children's CSWL abilities. Participants were presented with three types of stimuli in this task: novel objects, novel words, and attention getters (Fig. 1). The novel objects were photographs of novel items used in previous studies on CSWL (Vlach & Johnson, 2013; Vlach & Sandhofer, 2014). Each novel object was randomly paired with a novel word (e.g., "dax") to form object label pairings that would be presented to all children in the experiment. The novel words were recorded by a female native speaker of English, adhered to English phonotactics, and have been used in previous research on CSWL (Vlach & Johnson, 2013; Vlach & Sandhofer, 2014). The novel words presented in the training phase were: gaz, kiv, lep, tal, pif, jic, vul, urr, and fup. The novel words presented in the learning phase were: gip, wug, kib, lor, paf, yos, bif, zim, jat, rin, fep, hux. Attention getters consisted of a picture of a known entity (e.g., a baby) and a non-linguistic sound (e.g., a baby giggling).

Training phase. The CSWL task started with the training phase. The training phase was designed to familiarize children with the task and demonstrate how it would be ambiguous as to which words went with which objects during one learning trial. The experimenter began the training phase by saying, "I'm going to show you some pictures, so please pay attention to the screen." In each training trial, children were presented with two learning trials and one test trial (Fig. 1A). In the first learning trial, children saw two novel objects side by side on the screen while hearing two novel words (e.g., "gaz, kiv"). The presentation order of the objects (left/right side) and words (first/second) was randomly assigned. Each novel word was presented for 1 s, with a .5 s silence between each word. There was .25 s of silence at the beginning and end of the trial, resulting in a total duration of 3 s for the learning trial. Immediately following the first learning trial, children were presented with a second learning trial. The second learning trial had the same structure as the first learning trial. However, one of the words and one of the objects presented during the second learning trial were also presented on the first learning trial.

After the second learning trial, children were presented with a test trial. Children were presented with two objects: one that was novel and one that had been presented during both learning trials. The experimenter asked children to point to the object that had co-occurred with a word presented during the learning trials. For example, the experimenter would say, "Which one is the gaz?" The experimenter would record children's answers on a piece of paper and then proceed to the next training trial. Children were presented with training trials until children correctly answered five test trials in a row or completed ten test trials.

Learning phase. After the training phase was finished, the experimenter presented the learning phase. During the learning phase, participants were presented with 36 learning trials and 12 attention getter trials. Each learning trial consisted of two novel words and two novel objects. The presentation order of the objects (left/right side) and words (first/second) was randomly assigned. Each novel word was presented for 1 s, with a .5 s silence between each word. There was .25 s of silence at the beginning and end of the trial, resulting in a total duration of 3 s for the learning trial. The learning trials were presented in immediate succession, with an attention getter presented between every three trials. The attention getters were designed to reorient children's visual attention back to the screen and had a duration of 3 s.

There were a total of 12 novel words and 12 novel objects presented during the learning phase, which were randomly assigned into 12 novel word-object pairings. That is, each time that an object was presented during learning, the corresponding word always co-occurred. The word-object pairings were presented six times over the course of the learning phase.

The learning phase was organized into a block design, consisting of six blocks of learning and attention getter trials (Fig. 1). In this design, six of the word-object pairings were randomly assigned to be presented on a massed schedule and six were randomly assigned to be presented on an interleaved schedule. Massed word-object pairings were presented on consecutive learning trials, for six trials. Interleaved word-object pairings were presented in the same position (e.g., first learning trial of every block) in each of the six blocks. This ensured that all of the interleaved word-object pairings were presented an equal number of times (six presentations) and had an equal amount of time between each of the presentations (21 s).

Testing phase. After the learning phase, children were immediately presented with the testing phase. During the testing phase, there were a total of 12 test trials and 12 attention getter trials. An attention getter trial was presented in between each of the test trials to reorient children's attention to the screen. Each of the 12 test trials consisted of two novel objects on the monitor's screen, the target object and the foil object. The foil object was another object presented during the learning phase. The experimenter asked children to point to the target object. For example, the experimenter would say, "Which one is the zim?" The experimenter would record children's answers on a piece of paper and then proceed to the next test trial, until all test trials were complete.

Paired-associates memory task. Children's recognition memory abilities were tested in a paired-associates task (Fig. 2). The stimuli were drawings of common objects and were chosen from a standardized set of pictures normed for name agreement, image agreement, familiarity, and visual complexity (Snodgrass & Vanderwart, 1980). The names of the objects presented in the task were words that children typically comprehend and produce early in development (Fenson et al., 1994).

A paired-associates memory task was chosen as the measure of memory abilities for several reasons. First, a paired-associate memory paradigm has been used to assess children's general memory abilities for decades (e.g., Dilley & Paivio, 1968; Jones, 1973). Second, the paired-associates task has comparable task demands to the CSWL task and PPVT. Children are asked to view images and then select via pointing a single referent/picture at test in both tasks. Because the design of the current paired-associates task is similar to the other two tasks, it minimized the degree to which task demands contributed to the variance in the performance across the three tasks.

Training phase. The paired-associates memory task started with the training phase. The training phase was designed to familiarize children with the task and testing procedure. The experimenter began the task by saying, "I'm going to show you some pictures, so please pay attention to the screen." On each learning trial, children were presented with two objects for 4 s (Fig. 2A). No auditory or linguistic labels were provided for the objects. Immediately following each learning trial, a test trial was presented to children. Each test trial consisted of one object from the learning trial centered at the top of the screen and three objects oriented along the bottom of the screen. One of the three objects on the bottom of the screen was presented during the previous learning trial. The two foil objects had not be presented to the children during any other part of the experiment. The experimenter then prompted children to recognize the object pair presented during learning by asking, "Which of these pictures went with this picture?" and pointing to the picture at the top of the screen and then the three objects at the bottom of the screen. The experimenter would record children's answers on a piece of paper and then proceed to the next training trial. The experimenter continued to present learning and test trials until children correctly answered five test trials in a row or completed ten test trials.

Learning phase. The learning phase began immediately following the training phase. The experimenter started the learning phase by repeating the same instructions from the training phase, "I'm going to show you some pictures, so please pay attention to the screen." Children were then presented with 10 learning trials, which occurred in immediate succession (Fig. 2B). The structure of each learning trial was the same as the structure of the learning trials in the training phase. A new set of objects that had not been presented during the training phase were used during the learning phase.

Testing phase. Immediately following the learning phase, the experimenter presented children with 10 test trials. The test trials tested recognition memory for picture pairs presented during the learning phase. Each object pair was tested once, in the same order presented during the learning phase to ensure equivalent retention intervals for each of the objects (Fig. 2C). The procedure and structure of test trials was the same as the test trials in the training phase.

Results and discussion

The central goal of this experiment was to determine whether children's CSWL abilities are related to their age, memory, and/or language abilities. We started our analyses by examining performance on each of the three tasks in the experiment. Performance on the CSWL task was calculated by summing the number of correct responses at test for massed and interleaved word-object pairings. A paired samples t-test revealed no significant difference in performance between massed and interleaved word-object pairings at final test, $p > .10$. The finding that there are no overall differences between massed and interleaved items at an immediate post-test replicates previous research on children's CSWL (Smith & Yu, 2013; Vlach & Johnson, 2013). We also examined the possibility of ordering effects across massed and interleaved items. Within-subjects t-tests between the massed items, with Bonferroni corrections, revealed that children had higher performance on the first massed item presented than all of the other massed items, $ps < .05$. This finding potentially reflects a primacy effect (e.g., Atkinson, Hansen, & Bernnach, 1964). Within-subjects t-tests between the interleaved items, with Bonferroni corrections, revealed no significant differences, $ps > .10$. Finally, between-subjects t-tests did not reveal ordering effects of task presentation (e.g., CSWL task presented first vs. last), $ps > .10$. The massed and interleaved test items were summed to calculate overall performance on the CSWL task.

Performance on the paired-associates memory task was calculated by summing the number of correct responses at test. A Spearman-Brown coefficient of split-half reliability, comparing the first and second halves of the test items, revealed that the paired-associates memory task had strong internal consistency ($r = .789$). Performance on the PPVT was calculated using the raw scoring procedure outlined in the PPVT manual (Dunn & Dunn, 2007). We also examined whether performance on the CSWL and paired-associates memory tasks was significantly above chance performance, which was determined to be 6 out of 12 for the CSWL task and 3.33 out of 10 for the paired-associates memory task. One sample t-tests revealed that performance on both tasks was significantly higher than chance performance, $ps < .05$. The descriptive statistics and intercorrelations are presented in Table 1. Scatterplots of children's CSWL performance in relation to their PPVT performance, paired-associates performance, and age can be found in Fig. 3.

To examine whether memory and/or language abilities were uniquely contributing to CSWL performance, above and beyond age, we conducted a series of regression analyses. The regression models, with CSWL performance as the outcome measure, are presented in Table 2. In all models except Model 1C, children's age was entered into the regression analysis in Step 1. In Model 1A, PPVT raw score was entered in Step 2. In Model 1B, paired-associates memory performance was entered in Step 2. Finally, in Model 2, both PPVT raw score and paired-associates memory performance were entered in Step 2. The key finding from these analyses is that both language and memory

Table 1
Descriptive statistics and Pearson's r intercorrelations for variables in Experiment 1.

	M	*SD*	Range	1	2	3	4
1. Age (months)	46.43	5.41	22–66	1			
2. CSWL	6.70	2.37	4–12	.422*	1		
3. PPVT (raw score)	76.09	32.70	17–126	.789*	.568*	1	
4. Paired-Associates Memory	5.66	2.71	2–10	.483*	.708*	.598*	1

Note. $N = 47$ participants. Performance on the CSWL task was out of 12 and performance on the paired-associates memory task was out of 10.
* Indicates $p < .05$.

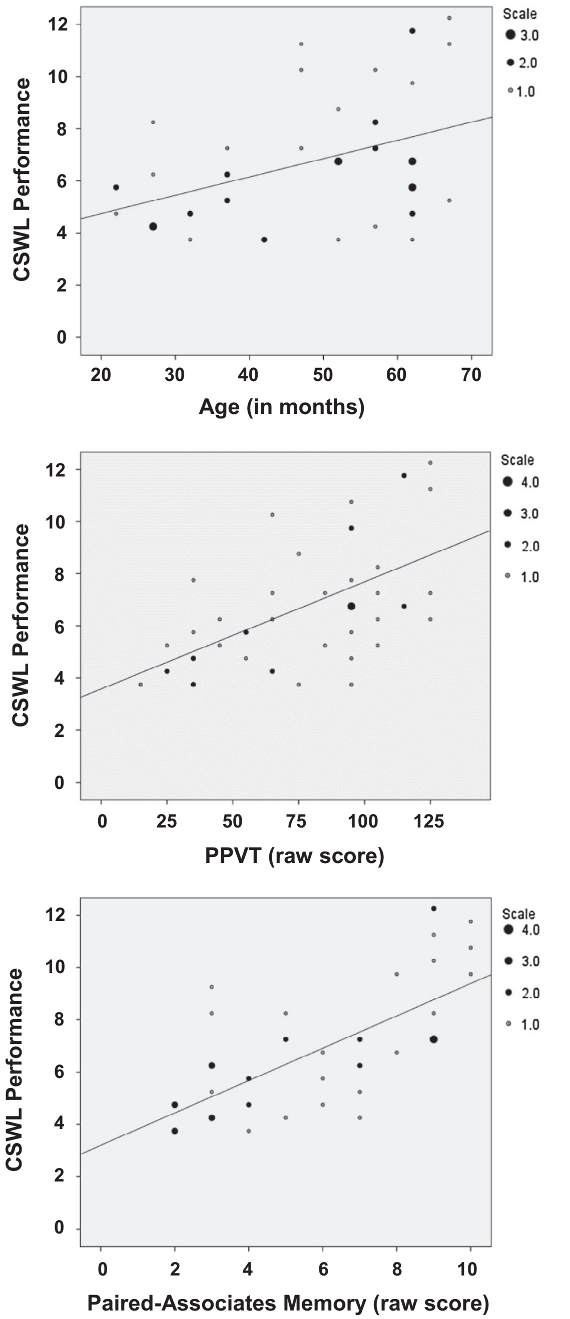

Fig. 3. Scatterplots with best fit lines for each factor (children's age, PPVT performance, and paired-associates memory performance) in relation to CSWL performance in Experiment 1. Dots are scaled in size; larger dots represent more data points (e.g., 3.0 size = 3 participants).

abilities predicted CSWL performance above and beyond age. Memory abilities predicted CSWL above and beyond age and language abilities. In fact, when age was not entered into the model (Model 1C), the model accounted for a comparable amount of variance as when age was in the model (Model 2). Thus, these results confirm previous research hypothesizing that young learners' CSWL is highly related to their memory abilities, perhaps to a greater degree than their age and/or language abilities (for a discussion, see Vlach & Johnson, 2013).

Although the results of Experiment 1 suggest that memory abilities are driving individual and developmental differences in children's CSWL, it is unclear whether global or specific memory abilities are contributing to performance. What types of memory abilities are supporting and/or constraining children's CSWL? A developmental systems theory would predict that multiple subprocesses of a cognitive system contribute to learning and development. That is, a single cognitive system (e.g., memory) operates as a series of smaller systems (e.g., short- vs. long-term memory, memory for different types of information, etc.). Experiment 2 further tested the predictions of a developmental systems theory by examining whether multiple memory abilities predict children's CSWL above and beyond age.

There are several types of recognition memory that could be facilitating word mapping. For instance, having strong recognition memory for the novel words heard and novel objects seen on each learning trial could support inferring word mappings later. Moreover, remembering when words and objects co-occurred (i.e., binding items together in time) may also help children to resolve ambiguity and later infer word mappings. Indeed, there are a plethora of memory processes that likely support CSWL beyond a single learning trial (e.g., long-term memory processes). Experiment 2 takes a first step in outlining the co-contributions of memory processes by examining whether three multiple memory abilities, which are likely important during a single learning event, predict children's CSWL: recognition memory for words, recognition memory for objects, and memory for word-object binding.

Experiment 2

This experiment examined whether one or multiple memory abilities facilitate children's CSWL. Children were presented with a CSWL task and three memory tasks: an object recognition memory, a word recognition memory, and a word-object binding memory task. In line with a developmental systems perspective, we hypothesized that, above and beyond age, multiple memory abilities would contribute to CSWL performance.

Methods

Participants

The participants were 53 preschool-aged children (M_{age} = 51.49 months; range: 31–68 months; 31 girls). Children were recruited from local day care centers and preschools. Children at this point in development were chosen to mirror the age of children that participated in Experiment 1. An additional 26 children participated in the study but were not included in the final sample because of fussiness (e.g., inability to sit still, running away from experimenter, etc.) and/or inability to follow directions during the experiment (e.g., not looking at the screen for more than 30 s, always choosing object on right side of screen at test, etc.). This attrition rate (32%) is lower than

Table 2
Hierarchical regression analyses for Experiment 1.

	R^2	ΔR^2	b	SE_b	β
Model 1A: Age & PPVT					
Step 1	.178	.178*			
Age (in months)			.070	.022	.422*
Step 2	.324	.146*			
Age (in months)			−.011	.034	−.069
PPVT (raw score)			.045	.015	.622*
Model 1B: Age & Paired-Associates Memory					
Step 1	.178	.178*			
Age (in months)			.070	.022	.422*
Step 2	.510	.332*			
Age (in months)			.017	.020	.104
Paired-Associates Memory (raw score)			.574	.105	.658*
Model 1C: PPVT & Paired-Associates Memory					
Step 1	.322	.322*			
PPVT (raw score)			.041	.009	.568*
Step 2	.534	.212*			
PPVT (raw score)			.016	.009	.225+
Paired-Associates Memory (raw score)			.501	.112	.574*
Model 2: Age, PPVT, & Paired-Associates Memory					
Step 1	.178	.178*			
Age (in months)			.070	.022	.422*
Step 2	.537	.359*			
Age (in months)			−.014	.028	−.087
PPVT (raw score)			.021	.013	.292
Paired-Associates Memory (raw score)			.502	.113	.576*

Note. Predictor variable in all models: Performance on CSWL task.
* Indicates $p < .05$.
+ Indicates $.05 < p < .10$.

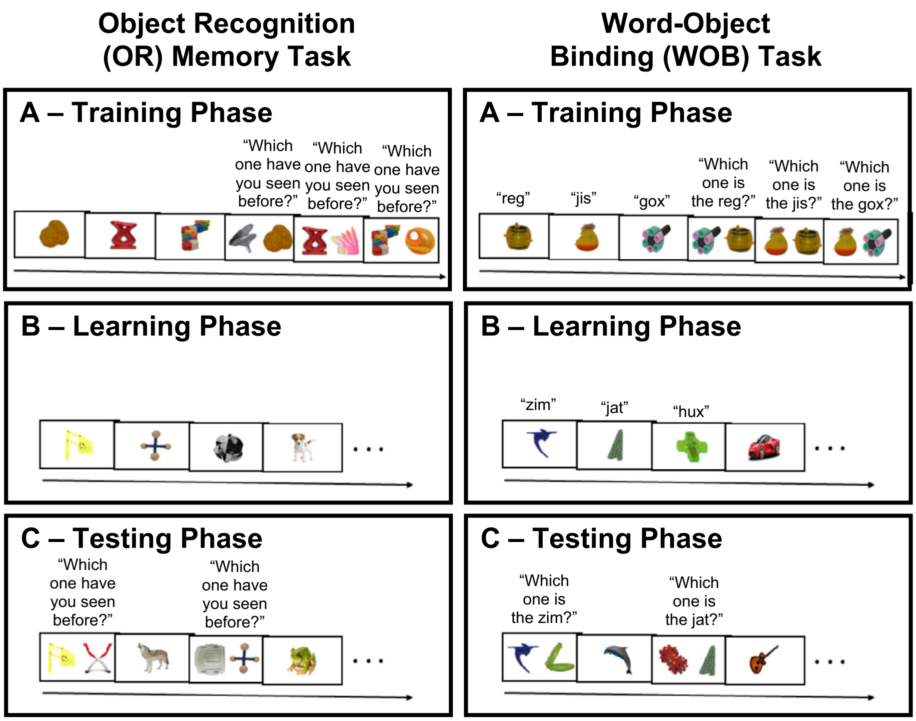

Fig. 4. Examples of stimuli used during the training (Panels A), learning (Panels B), and testing (Panels C) phases of the object recognition memory and word-object binding tasks used in Experiment 2. All objects and/or words presented in the learning phase were tested in the testing phase. The WR task is not depicted because no visual stimuli were presented. The WR task followed the same general structure as the OR and WOB tasks; the task also consisted of a training, learning, and testing phase.

or comparable with prior studies on children's CSWL (Vouloumanos & Werker, 2009; Yu & Smith, 2011). Children received a storybook as a thank you for their participation. The children that participated in Experiment 2 had not participated in Experiment 1.

Apparatus & stimuli

The experiment was administered on a laptop or iPad. As can be seen in Figs. 1 and 4, visual stimuli consisted of pictures of objects presented on the laptop or iPad screen. Images and pictures were approximately 3.3″ and 2.75″ in size and presented at a resolution of 640 × 480. For learning trials with one image, the image was centered on the screen. For learning trials with two images, there was an average 2″ spacing between images. Auditory stimuli were presented to children using the laptop or iPad speakers at approximately 75 dB. The presentation timing of the stimuli was controlled by Keynote. The stimuli consisted of novel words from prior studies of CSWL (Vlach & Sandhofer, 2014) and the NOUN database of novel words (Horst & Hout, 2015). Each word and object was only used in one task of the experiment. In all tasks, an attention getter trial was presented between every three learning trials and every test trial to keep children on task.

Design

All children participated in four tasks: a cross-situational word learning (CSWL) task, an object recognition memory task (OR), a word recognition memory task (WR), and a word-object binding memory task (WOB) task.

Procedure

The ordering of the three memory tasks (OR, WR, and WOB tasks) was randomly assigned for each participant. The presentation order of the CSWL task was counterbalanced across participants; the CSWL task was either the first task or last task of the experiment. The experiment began with the first task and ended with the completion of the fourth task. The duration of the entire experiment was about 35 min.

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

Object Recognition (OR) Memory Task. This task assessed children's visual recognition memory abilities for unnamed novel objects (Fig. 4).

Training phase. The OR task started with the training phase. The training phase was designed to familiarize children with the task and testing procedure. The experimenter began the task by saying, "I'm going to show you some pictures, so please pay attention to the screen." Children were then presented with three learning trials in immediate succession (Fig. 4A, left). Each learning trial consisted of a novel object presented in the center of the screen and lasted for 3 s. Linguistic labels were not presented with the objects. Immediately following the learning trials, the experimenter presented three test trials in immediate succession. Each test trial presented children with two objects; one of the objects had been presented during learning and one object had not been presented before in the experiment. The experimenter asked, "Which of these pictures have you seen before?" and then recorded children's answers on a piece of paper.

Learning phase. Immediately following the training phase, the experimenter presented the learning phase. The experimenter began the task by saying, "I'm going to show you some pictures, so please pay attention to the screen." Children were then presented with 12 learning trials, presented in immediate succession (Fig. 4B, left). The structure and duration of the learning trials was the same as the training phase, but a different set of novel objects was used.

Testing phase. After the learning phase was complete, the experimenter presented children with 12 test trials. Memory for each object was tested once, in the same order presented during the learning phase to ensure equivalent retention intervals for each of the objects (Fig. 4C, left). The structure and duration of the test trials was the same as the training phase, but a different set of novel objects was used.

Word Recognition Memory (WR) Task. This task assessed children's auditory recognition memory for novel words. The novel words were recorded by the same female speaker who produced the words for the CSWL task. The novel words presented during training were: zun, seb, and guf. The novel words presented during learning were: cad, zar, val, ged, fem, nur, sus, teb, mig, lir, yop, and gam.

Table 3
Descriptive statistics and Pearson's r intercorrelations for variables in Experiment 2.

	M	*SD*	Range	1	2	3	4	5
1. Age (months)	51.49	11.00	31–68	1				
2. CSWL	7.64	2.01	4–12	.269⁺	1			
3. OR Task	9.11	2.85	3–12	.421*	.488*	1		
4. WR Task	6.79	1.93	3–12	.148	.452*	.268⁺	1	
5. WOB Task	7.06	2.44	2–12	.395*	.554*	.470*	.355*	1

Note. $N = 53$ participants. Performance on the CSWL, OR, WR, and WOB tasks was out of 12.
* Indicates $p < .05$.
⁺ Indicates $.05 < p < .10$.

Training phase. The WR task started with the training phase. The training phase was designed to familiarize children with the task and testing procedure. The task began with the experimenter saying, "You are going to hear some words on a video, so pay attention." Children were then presented with three novel words (e.g., "dax"), one per learning trial. The novel words were presented once and had a duration of 1 s. Each novel word was separated by 2 s of silence, resulting in a total learning trial duration of 3 s. There were no visual stimuli presented on the iPad screen (i.e., blank white screen). After presenting the three novel words, children were presented with three test trials. In each test trial, the experimenter presented children with a novel word, by saying "Listen to this word: dax." The experimenter then asked, "Is dax a word from the video, or is dax a new word, not from the video?" Two of the test trials tested children's memory for learned words (i.e., from the video was the correct answer) and one test trial presented children with an unfamiliar novel word (i.e., new word/not from the video was the correct answer). The experimenter recorded children's responses on a piece of paper.

Learning phase. Immediately following the training phase, the experimenter presented the learning phase. The experimenter began the task by saying, "You are going to hear some words on a video, so pay attention." Children were then presented with 12 learning trials, presented in immediate succession. The structure and duration of the learning trials was the same as the training phase, but a different set of novel words was used.

Testing phase. After the learning phase was complete, the experimenter presented children with 12 test trials. In six of the test trials, children were presented with a familiar word from the learning phase. The remaining six trials presented children with unfamiliar words not presented during the learning phase, with the order of test trials counterbalanced. The structure and duration of the test trials was the same as the training phase, but a different set of novel objects was used.

Word-Object Binding (WOB) Memory Task. This task assessed children's recognition memory for novel word-object pairings. The novel words were recorded by the same female speaker who produced the words for the CSWL and WR tasks. The novel words presented during training were: reg, gis, and gox. The novel words presented during learning were: yun, veb, pid, vam, dar, tig, zat, pax, kas, sug, wut, and jaf. The stimuli used in this task were not used in any other task of the experiment.

Training phase. The WOB task started with the training phase. The training phase was designed to familiarize children with the task and testing procedure. The experimenter began the task by saying, "I'm going to show you pictures with words, so pay attention." Children were then presented with three learning trials, presented in immediate succession (Fig. 4A, right). Each learning trial consisted of a novel object presented in the center of the screen and lasted for 3 s. Linguistic labels (e.g., "reg") were simultaneously presented with each of the objects at the beginning of the trial and had a duration of 1 s. Immediately following the learning trials, the experimenter presented three test trials in immediate succession. Each test trial presented children with two objects, both of which had been presented during the learning trials. The experimenter asked, "Which one is the reg?" and then recorded children's answers on a piece of paper.

Learning phase. Immediately following this training phase, the experimenter presented the learning phase. The experimenter began the task by saying, "I'm going to show you pictures with words, so pay attention." Children were then presented with 12 learning trials, presented in immediate succession. The structure and duration of the learning trials was the same as the training phase, but a different set of novel words was used.

Testing phase. After the learning phase was complete, the experimenter presented children with 12 test trials. Memory for each word-object pairing was tested once, in the same order presented during the learning phase to ensure equivalent retention intervals for each of the objects (Fig. 4C, right). The structure and duration of the test trials was the same as the training phase, but a different set of novel objects was used.

Results & discussion

The central goal of this study was to further test hypotheses of a developmental systems theory by determining whether children's CSWL abilities are related to one or multiple memory abilities that support word mapping in one moment in time (i.e., in one learning trial). We started our analyses by examining performance on each of the four tasks in the study. Performance on the CSWL task was calculated by summing the number of correct responses at test for massed and interleaved word-object pairings. A paired samples *t*-test revealed no significant difference in performance between massed and interleaved word-object pairings at final test, $p > .10$. All the ordering effect analyses conducted in Experiment 1 were also conducted for Experiment 2, and did not reveal any significant ordering effects, $ps > .10$. Moreover, the higher performance on the first massed item observed in Experiment 1 was not replicated in Experiment 2. The massed and interleaved test items were summed to calculate overall performance on the CSWL task.

Performance on the OR, WR, and WOB tasks was calculated by summing the number of correct responses at test. We also examined whether performance on the CSWL, OR, WR, and WOB tasks was significantly above chance performance, which was determined to be 6 out of 12 for all tasks. One sample t-tests revealed that performance on all tasks was significantly higher than chance performance, $ps < .05$. The descriptive statistics and intercorrelations are presented in Table 3. Scatterplots of children's CSWL performance in relation to age, OR performance, WR performance, and WOB performance can be found in Fig. 5.

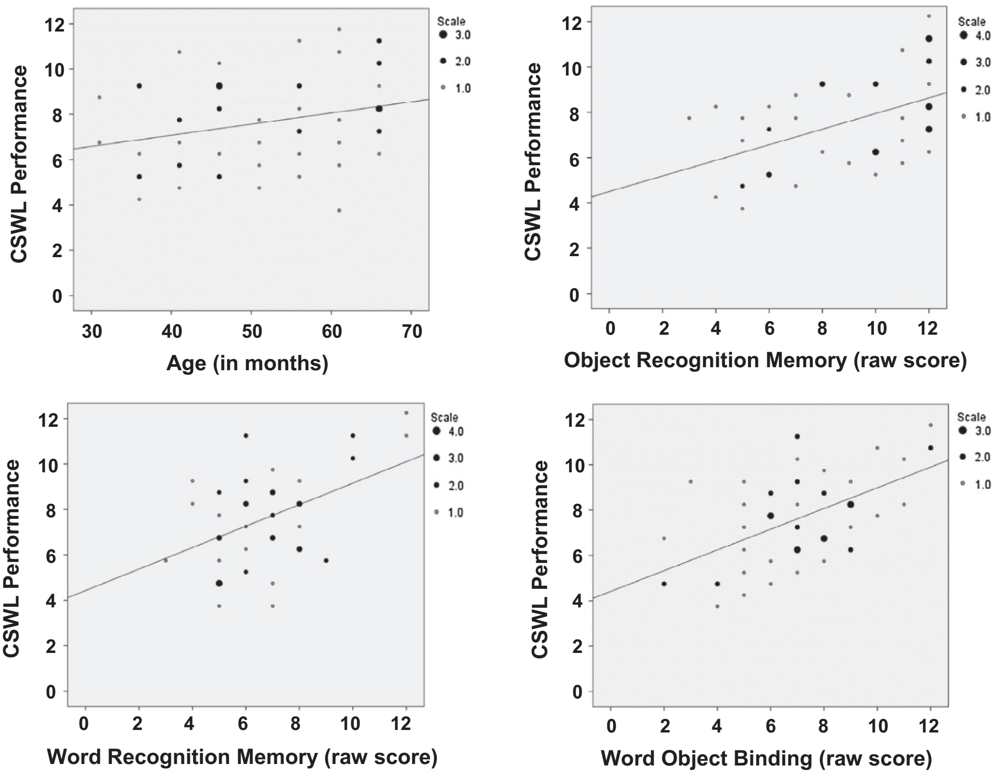

Fig. 5. Scatterplots with best fit lines for each factor (children's age, OR performance, WR performance, and WOB performance) in relation to CSWL performance in Experiment 2. Dots are scaled in size; larger dots represent more data points (e.g., 2.0 size = 2 participants).

To examine whether one and/or multiple memory abilities were uniquely contributing to CSWL performance, above and beyond age, we conducted a series of regression analyses. The regression models, with CSWL performance as the outcome measure, are presented in Table 4. In all models except Model 2, children's age was entered into the regression analysis in Step 1. In Models 1A–1C, one of the three memory tasks (OR, WR, or WOB) was entered in Step 2. In Model 3, all three memory tasks (OR, WR, & WOB) were entered in Step 2. The key finding from these analyses is that each of the three memory tasks predicted CSWL performance above and beyond age. Moreover, when all tasks were entered into the model, each task uniquely predicted CSWL performance above and beyond age and the other memory tasks. In fact, when age was not entered into the model (Model 2), the model accounted for a comparable amount of variance as when age was in the model (Model 3). Thus, these results confirm the hypothesis that not one, but multiple memory abilities support children's CSWL. The theoretical implications of these findings will be outlined in Section 'General discussion'.

General discussion

Researchers have studied children's CSWL to understand the cognitive processes that drive individual and developmental differences in language development. The current work tested several theoretical accounts of CSWL and, in turn, demonstrated that multiple cognitive systems facilitate children's CSWL. In particular, Experiment 1 revealed that general language and memory abilities contribute to children's CSWL performance. Moreover, Experiment 2 demonstrated that not one, but multiple memory abilities, contribute to CSWL performance. All of these cognitive abilities were predictive of children's CSWL performance above and beyond age.

Taken together, these studies yield two important theoretical contributions to our understanding of CSWL. First, this work provides evidence against a maturational account of CSWL. Children's age was the least compelling predictor of children's performance, and the relation was no longer present when considering children's language and memory abilities. Second, this work provides strong evidence for a developmental systems theory of CSWL: multiple cognitive systems, and multiple processes within one system (i.e., memory for words and objects, binding, etc.), uniquely contribute to performance. Thus, this research has important implications for computational models of CSWL, which currently do not account for changes in children's cognitive capacities across time. In particular, computational models that take a developmental systems perspective are likely to yield richer, more accurate characterizations of word learning and language development.

Table 4
Hierarchical regression analyses for Experiment 2.

	R^2	ΔR^2	b	SE_b	β
Model 1A: Age & OR					
Step 1	.072	.072^{+}			
Age (in months)			.049	.025	.269^{+}
Step 2	.243	.171*			
Age (in months)			.014	.025	.077
OR Task (raw score)			.322	.096	.455*
Model 1B: Age & WR					
Step 1	.072	.072^{+}			
Age (in months)			.049	.025	.269^{+}
Step 2					
Age (in months)	.246	.174*			
WR Task (raw score)			.038	.023	.206
			.441	.130	.422*
Model 1C: Age & WOB					
Step 1	.072	.072^{+}			
Age (in months)			.049	.025	.269^{+}
Step 2	.310	.282*			
Age (in months)			.011	.023	.060
WOB Task (raw score)			.437	.106	.530*
Model 2: OR, WR & WOB					
Step 1					
WOB Task (raw score)	.307	.307*			
			.457	.096	.554*
Step 2	.433	.126*			
OR Task (raw score)			.182	.087	.258*
WR Task (raw score)			.275	.121	.263*
WOB Task (raw score)			.280	.104	.339*
Model 3: Age, OR, WR & WOB					
Step 1	.072	.072^{+}			
Age (in months)			.049	.025	.269^{+}
Step 2	.433	.361*			
Age (in months)			−.003	.023	−.016
OR Task (raw score)			.186	.092	.263*
WR Task (raw score)			.274	.122	.263*
WOB Task (raw score)			.283	.109	.343*

Note. Predictor variable in all models: Performance on CSWL task.
* Indicates $p < .05$.
$^{+}$ Indicates $.05 < p < .10$.

Why and how are language and memory abilities important for CSWL?

The strongest predictor of CSWL performance in Experiment 1 was children's memory abilities, suggesting an integral role of memory development in CSWL. Indeed, there is a lot of information to remember during CSWL. In the context of a single word learning event, children must remember visual information (i.e., the objects they see), auditory information (i.e., the words they hear), and bind visual and auditory information together in time (i.e., potential word-object mappings). The results of Experiment 2 confirmed that each of these task-specific memory abilities uniquely contributes to children's CSWL. As children gain more experience learning words, the amount of information that children must remember multiplies with each learning event. Thus it is unlikely that task-specific memory abilities are solely driving the development of CSWL; global memory abilities, such as the general amount of information that children can remember across time, are also likely to be important for successful CSWL.

Experiment 1 also demonstrated that language abilities uniquely contributed to children's CSWL performance. This finding suggests an important role of children's language history in supporting the learning of new words. As children gain more practice learning words, they may be more likely to learn new words faster and in more challenging learning environments (Scott & Fisher, 2012; Smith & Yu, 2013). Given that CSWL is a language learning task, it is unsurprising that children's language abilities are related to their performance. However, what may seem surprising is that children's language abilities were a less important predictor of CSWL performance than children's memory abilities.

Why were memory abilities the strongest predictor of children's CSWL? There are several explanations for why memory abilities may be a/the primary cognitive capacity driving the development of CSWL. First, as described above, CSWL places a large demand on children's memory abilities. CSWL may be more taxing of the memory system (s) than other cognitive systems, such as language. Second, language abilities may play a particularly large role in only one component of CSWL, rather than the entire process. For instance, language abilities may support the organization of words into linguistic structures and representations, supporting retrieval and use of learned words. However, language history may play a smaller role in supporting the acquisition of novel words presented out of this linguistic context. Indeed, a next step for future research is to identify how the relative contributions of language and memory abilities fluctuate across learning environments, such as in more rich linguistic and social learning contexts.

Although children's language and memory abilities accounted for a sizeable amount of the variance in children's CSWL performance, there was remaining variance that the regression models could not explain. We predict that additional language and memory processes will explain the remaining variance. For instance, the current studies did not examine whether children's CSWL is related to long-term memory abilities. In naturalistic language learning environments, children must retain and retrieve knowledge across extended timescales, such as days, weeks, and months at a time. Children forget a considerable amount of information while learning words (Vlach, 2014; Vlach & Sandhofer, 2012), but also consolidate linguistic information during sleep (Gómez, Bootzin, & Nadel, 2006; Hupbach, Gomez, Bootzin, & Nadel, 2009). Indeed, long-term memory processes are important for language learning across time and future research should examine whether long-term memory abilities contribute to the development of CSWL.

We also predict that other cognitive systems will explain the remaining variance in the regression models. For instance, a theoretical account not tested in the current research is the visual attention account. According to this account, as children get better at focusing their attention to objects in the world, they selectively shift their gaze to relevant information when hearing new and learned words. For instance, in one study (Yu & Smith, 2011), infants were divided into two groups: infants that had stronger performance at test and infants that had weaker performance at test. The stronger learners looked more often to the correct referent during learning relative to the weaker learners. These results have led researchers to conclude that visual attention during learning contributes to individual and developmental differences in CSWL. Future research should test whether visual attention plays a role in the development of CSWL, above and beyond age and other cognitive systems. Indeed, an important direction in any developmental systems theory is to continually refine and re-define the systems that drive development (for reviews, see Smith & Thelen, 2003; Van Geert, 1991).

Implications for theories of CSWL and language development

CSWL is typically characterized by two classes of language development theories and computational models: associative learning accounts (e.g., Smith & Yu, 2008; Yu & Smith, 2011) and hypothesis testing accounts (e.g., Trueswell et al., 2013; Vouloumanos & Werker, 2009; Xu & Tenenbaum, 2007; for reviews, see Yu & Smith, 2012; Yurovsky & Frank, 2015). According to associative learning accounts, learners encode co-occurrence probabilities that eventually develop into a matrix of word–referent associations, which are then used to make inferences about the meaning of words. Alternatively, hypothesis testing accounts propose that learners generate hypotheses about word-referent mappings, encode the current evidence in relation to the hypotheses, and then select among hypotheses to make inferences about the meaning of words. In brief, these theories have focused on explaining the process of word mapping and generalization.

The current research identifies an important next step in this line of work: to use a developmental systems perspective to build upon existing models of CSWL. In particular, we suggest that models be expanded to incorporate children's changing cognitive abilities as variables that contribute to, and perhaps determine, learning processes and outcomes. One possible new direction is to construct computational models that characterize broad developmental changes in word learning due to cognitive abilities (i.e., language and memory abilities) and children's age. For instance, creating a computational model that predicts CSWL performance as a product of a learning process (e.g., associative matrix and/or hypotheses), children's age, language abilities, and memory abilities, would be a fruitful first step in this direction. Indeed, these models may be more accurate in predicting CSWL performance than models that do not consider changes in children's developmental state.

Another next step is to examine the contribution of individual children's developmental state in determining the structure of associative matrices and hypotheses. We predict that children's individual developmental state, not the learning process per se, may determine the data set by which children make inferences about the meaning of words. For instance, one particular child may have poor auditory recognition memory abilities (i.e., poor memory for words) and stronger visual recognition memory abilities (i.e., stronger memory for objects). For this child, associative matrices and/or hypotheses may be more heavily grounded in visual information than auditory information. As this child's memory abilities develop, the child may have a reversal in memory abilities, where their auditory memory abilities improve and are stronger than their visual recognition memory abilities. In this case, changes to associative matrices and hypotheses are more likely to be determined by auditory information than visual information. In brief, computational models of CSWL should consider children's cognitive capacities as a determining factor in the data set that children encode, store, and later retrieve when making word-referent inferences. We predict that these data sets will be highly dynamic across development and grounded in the cognitive abilities of the learner. Indeed, children are unlikely to be able to attend to, encode, and remember all of the information that the world presents them. Thus, they will need to make the most of their strengths (and overcome limitations) in order to learn word-referent mappings.

In conclusion, multiple cognitive systems, such as language and memory, are likely contributing to individual and developmental differences in CSWL. As suggested by the results of the current work, children's language and memory abilities are important cognitive systems for CSWL. Future research should continue to examine how these and other cognitive systems (e.g., visual attention) co-contribute to word learning. Indeed, a developmental systems theory is likely to best account for how children's cognitive abilities facilitate CSWL and language development.

Acknowledgments

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

References

Atkinson, R. C., Hansen, D. N., & Bernnach, H. A. (1964). Short-term memory with young children. *Psychonomic Science, 1*, 255–256. http://dx.doi.org/10.3758/BF03342896.
Carey, S., & Bartlett, E. (1978). Acquiring a single new word. *Proceedings of the Stanford Child Language Conference, 15*, 17–29.
Dilley, M. G., & Paivio, A. (1968). Pictures and words as stimulus and response items in paired-associate learning of young children. *Journal of Experimental Child Psychology, 6*, 231–240. http://dx.doi.org/10.1016/0022-0965(68)90087-8.
Dunn, L. M., & Dunn, D. M. (2007). *Peabody picture vocabulary test* (4th ed.). Minneapolis, MN: Pearson Assessments.
Fazly, A., Alishahi, A., & Stevenson, S. (2010). A probabilistic computational model of cross-situational word learning. *Cognitive Science, 34*, 1017–1063. http://dx.doi.org/10.1111/j.1551-6709.2010.01104.x.
Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., ... Stiles, J. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development*, i–185. http://dx.doi.org/10.2307/1166093.
Fitneva, S. A., & Christiansen, M. H. (2011). Looking in the wrong direction correlates with more accurate word learning. *Cognitive Science, 35*, 367–380. http://dx.doi.org/10.1111/j.1551-6709.2010.01156.x.
Gómez, R. L., Bootzin, R. R., & Nadel, L. (2006). Naps promote abstraction in language-learning infants. *Psychological Science, 17*, 670–674. http://dx.doi.org/10.1111/j.1467-9280.2006.01764.x.
Horst, J. S., & Hout, M. C. (2015). The Novel Object and Unusual Name (NOUN) Database: A collection of novel images for use in experimental research. *Behavior Research Methods, 10*, 1–17. http://dx.doi.org/10.3758/s13428-015-0647-3. Advanced publication.
Hupbach, A., Gomez, R. L., Bootzin, R. R., & Nadel, L. (2009). Nap-dependent learning in infants. *Developmental Science, 12*, 1007–1012. http://dx.doi.org/10.1111/j.1467-7687.2009.00837.x.
Jones, H. R. (1973). The use of visual and verbal memory processes by three-year-old children. *Journal of Experimental Child Psychology, 15*, 340–351. http://dx.doi.org/10.1016/0022-0965(73)90154-9.
Kachergis, G., Yu, C., & Shiffrin, R. M. (2013). Actively learning object names across ambiguous situations. *Topics in Cognitive Science, 5*, 200–213. http://dx.doi.org/10.1111/tops.12008.
Medina, T. N., Snedeker, J., Trueswell, J. C., & Gleitman, L. R. (2011). How words can and cannot be learned by observation. *Proceedings of the National Academy of Sciences, 108*, 9014–9019. http://dx.doi.org/10.1073/pnas.1105040108.
Miller, H. E., Vlach, H. A., & Simmering, V. R. (in press). Producing spatial words is not enough: Understanding the relation between language and spatial cognition. *Child Development*. http://dx.doi.org/10.1111/cdev.12664 (in press).
Newport, E. L. (1990). Maturational constraints on language learning. *Cognitive Science, 14*, 11–28. http://dx.doi.org/10.1207/s15516709cog1401_2.
Scott, R. M., & Fisher, C. (2012). 2.5-year-olds use cross-situational consistency to learn verbs under referential uncertainty. *Cognition, 122*, 163–180. http://dx.doi.org/10.1016/j.cognition.2011.10.010.
Smith, K., Smith, A. D. M., & Blythe, R. A. (2011). Cross-situational learning: An experimental study of word-learning mechanisms. *Cognitive Science, 35*, 480–498. http://dx.doi.org/10.1111/j.1551-6709.2010.01158.x.
Smith, L. B., & Thelen, E. (2003). Development as a dynamic system. *Trends in Cognitive Sciences, 7*, 343–348. http://dx.doi.org/10.1016/S1364-6613(03)00156-6.
Smith, L. B., & Yu, C. (2008). Infants rapidly learn word-referent mappings via cross-situational statistics. *Cognition, 106*, 1558–1568. http://dx.doi.org/10.1016/j.cognition.2007.06.010.
Smith, L. B., & Yu, C. (2013). Visual attention is not enough: Individual differences in statistical word-referent learning in infants. *Language Learning and Development, 9*, 25–49. http://dx.doi.org/10.1080/15475441.2012.707104.
Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6*, 174–215. http://dx.doi.org/10.1037/0278-7393.6.2.174.
Suanda, S. H., Mugwanya, N., & Namy, L. L. (2014). Cross-situational statistical word learning in young children. *Journal of Experimental Child Psychology, 126*, 395–411. http://dx.doi.org/10.1016/j.jecp.2014.06.003.
Trueswell, J. C., Medina, T. N., Hafri, A., & Gleitman, L. R. (2013). Propose but verify: Fast mapping meets cross-situational word learning. *Cognitive Psychology, 66*, 126–156. http://dx.doi.org/10.1016/j.cogpsych.2012.10.001.
Van Geert, P. (1991). A dynamic systems model of cognitive and language growth. *Psychological Review, 98*, 3–53. http://dx.doi.org/10.1037/0033-295X.98.1.3.
Vlach, H. A. (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. http://dx.doi.org/10.1111/cdep.12079.
Vlach, H. A., & Johnson, S. P. (2013). Memory constraints on infants' cross-situational statistical learning. *Cognition, 127*, 375–382. http://dx.doi.org/10.1016/j.cognition.2013.02.015.
Vlach, H. A., & Sandhofer, C. M. (2012). Fast mapping across time: Memory mechanisms support children's ability to retain words. *Frontiers in Psychology, 3*, 46. http://dx.doi.org/10.3389/fpsyg.2012.00046.
Vlach, H. A., & Sandhofer, C. M. (2014). Retrieval dynamics and retention in cross-situational statistical learning. *Cognitive Science, 38*, 757–774. http://dx.doi.org/10.1111/cogs.12092.
Vouloumanos, A., & Werker, J. F. (2009). Infants' learning of novel words in a stochastic environment. *Developmental Psychology, 45*, 1611–1617. http://dx.doi.org/10.1037/a0016134.
Woodard, K., Gleitman, L. R., & Trueswell, J. C. (2016). Two-and three-year-olds track a single meaning during word learning: Evidence for propose-but-verify. *Language Learning and Development, 12*, 252–261. http://dx.doi.org/10.1080/15475441.2016.1140581.
Xu, F., & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review, 114*, 245–272. http://dx.doi.org/10.1037/0033-295X.114.2.245.
Yu, C., & Smith, L. B. (2007). Rapid word learning under uncertainty via cross-situational statistics. *Psychological Science, 18*, 414–420. http://dx.doi.org/10.1111/j.1467-9280.2007.01915.x.
Yu, C., & Smith, L. B. (2011). What you learn is what you see: Using eye movements to study infant cross-situational word learning. *Developmental Science, 14*, 165–180. http://dx.doi.org/10.1111/j.1467-7687.2010.00958.x.
Yu, C., & Smith, L. B. (2012). Modeling cross-situational word-referent learning: Prior questions. *Psychological Review, 119*, 21–39. http://dx.doi.org/10.1037/a0026182.
Yurovsky, D., & Frank, M. C. (2015). An integrative account of constraints on cross-situational word learning. *Cognition, 145*, 53–62. http://dx.doi.org/10.1016/j.cognition.2015.07.013.
Yurovsky, D., Yu, C., & Smith, L. B. (2013). Competitive processes in cross-situational word learning. *Cognitive Science, 37*, 891–921. http://dx.doi.org/10.1111/cogs.12035.