Journal of Experimental Child Psychology 126 (2014) 395–411

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

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

Cross-situational statistical word learning in young children

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ARTICLE INFO

Article history:
Received 30 June 2013
Revised 4 June 2014
Available online 8 July 2014

Keywords:
Cross-Situational learning
Contextual diversity
Word learning
Vocabulary acquisition
Language development
Statistical learning

ABSTRACT

Recent empirical work has highlighted the potential role of cross-situational statistical word learning in children's early vocabulary development. In the current study, we tested 5- to 7-year-old children's cross-situational learning by presenting children with a series of ambiguous naming events containing multiple words and multiple referents. Children rapidly learned word-to-object mappings by attending to the co-occurrence regularities across these ambiguous naming events. The current study begins to address the mechanisms underlying children's learning by demonstrating that the diversity of learning contexts affects performance. The implications of the current findings for the role of cross-situational word learning at different points in development are discussed along with the methodological implications of employing school-aged children to test hypotheses regarding the mechanisms supporting early word learning.

Introduction

According to one estimate, by 6 years of age, children have amassed a vocabulary of 14,000 words (Carey, 1978). One central goal in the study of children's language acquisition is to better understand the processes that underlie such impressive word learning. Based on their influential investigation into these processes, Carey and Bartlett (1978) demonstrated one learning mechanism, *fast mapping,*

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http://dx.doi.org/10.1016/j.jecp.2014.06.003
0022-0965/

a learning process that occurs after a single exposure or a few exposures to a novel word and involves the acquisition of an initial link between a word and its referent. Much of the ensuing research on children's word learning over the past three and a half decades has been devoted to understanding the basis for fast mapping (for a discussion, see Swingley, 2010), including the nature of the constraints on the mapping process (see Woodward & Markman, 1998), whether fast mapping is specific to the domain of word learning (Markson & Bloom, 1997), and how the mapping processes change with development (Hollich et al., 2000).

Recently, a growing body of research has aimed to understand a different word learning process, one that *extends* over multiple encounters. In one such study employing adults as model word learners, Yu and Smith (2007) presented participants with a series of learning trials, each involving ambiguous reference. In each trial, participants viewed multiple pictures of objects simultaneously on a computer screen and heard multiple spoken words played sequentially in a random order. In each trial, it was unclear which words referred to which objects. However, over trials, every time participants heard a particular word, its corresponding referent object was present. Importantly, word–object pairs did not always appear with the same set of accompanying words and objects. Thus, participants could learn the words if they attended to the cross-situational regularities with which particular words and objects co-occurred. Yu and Smith found that adult learners were remarkably sensitive to these cross-situational co-occurrence patterns between words and objects (i.e., their co-occurrence statistics) and could use this knowledge to acquire the word-to-object mappings. Yu and Smith's data, as well as other results (e.g., Akhtar & Montague, 1999; Gillette, Gleitman, Gleitman, & Lederer, 1999; Vouloumanos, 2008), have highlighted the likely role of processes other than fast mapping in children's lexical acquisition.

Two lines of research have been inspired by Yu and Smith's initial work on cross-situational learning. First, a number of investigations have been devoted to extending the empirical phenomenon of cross-situational word learning to developmental populations. Toward this end, Smith and Yu (2008) designed a version of their adult cross-situational learning paradigm suitable for testing infant learners. Employing a simplified looking-based version of the task, Smith and Yu found that 12- to 14-month-old infants successfully associated words and their corresponding objects in a task that, like its adult precursor, required them to attend to the co-occurrence statistics across situations (see also Scott & Fisher, 2012; Smith & Yu, 2013; Vlach & Johnson, 2013; Vouloumanos & Werker, 2009; Yu & Smith, 2011). This finding—that even young word learners possess the capacity for cross-situational word learning—is important because it is an existence proof for the claim that a process such as cross-situational word learning can facilitate early lexical acquisition.

A second line of research has been devoted to understanding the underlying mechanisms that make cross-situational word learning possible. Toward this broad goal, a number of researchers have employed adult learners, as Yu and Smith originally did, to test the nature of the underlying learning algorithms that could explain successful cross-situational word learning (e.g., Kachergis, Yu, & Shiffrin, 2012; Smith, Smith, & Blythe, 2011; Trueswell, Medina, Hafri, & Gleitman, 2013; Yu, Zong, & Fricker, 2012; Yurovsky, Yu, & Smith, 2013). Extant computational and experimental work suggests that multiple mechanisms could explain cross-situational word learning findings, including hypothesis testing (Medina, Snedeker, Trueswell, & Gleitman, 2011; Trueswell et al., 2013), associative learning (Kachergis et al., 2012; Yu, 2008), and single-trial learning (Smith, Smith, & Blythe, 2009). Other researchers have examined the constellation of factors that influence adults' cross-situational word learning performance, demonstrating that the diversity of learning environments (Kachergis, Yu, & Shiffrin, 2009; Suanda & Namy, 2012), attention to competitors (Fitneva & Christiansen, 2011), the adoption of exclusion constraints (Yoshida, Rhemtulla, & Vouloumanos, 2012; Yurovsky et al., 2013), and the presence of grammatical cues (Monaghan & Mattock, 2012) all help in cross-situational word learning. Finally, researchers have also begun to examine the extent to which adult learners can acquire word-to-referent mappings through cross-situational learning while also solving other language-related tasks to better mimic the multitasking likely involved in young children's early language learning. Experimental research along these lines has revealed that adult learners can successfully learn words cross-situationally even when the words are presented in continuous speech and thus require learners to segment speech into the relevant units (Cunillera, Laine, Camara, & Rodriguez-Fornells, 2010; Yurovsky, Yu, & Smith, 2012).

Together, this recent wealth of studies has contributed to a better understanding of the nature of cross-situational word learning and its potential role in lexical acquisition. The goal of the current experiment was to examine cross-situational word learning in school-aged children between 5 and 7 years of age. There are two reasons why studying lexical development in this age group is important.

First, research with this age group may bridge the two sets of findings mentioned above. That is, research with adult learners that probe the mechanisms of cross-situational word learning employ research methodologies that would be difficult to implement with infants. These include paradigms that require adult learners to explicitly select mappings on a trial-by-trial basis (often from a large set of candidate objects; see Smith et al., 2011; Trueswell et al., 2013), paradigms that require adult learners to report confidence levels in their word-to-referent mappings (Vlach & Sandhofer, 2014; Yurovsky et al., 2013), and paradigms that require adult learners to actively select the word–object pairings to be seen on each trial (Kachergis, Yu, & Shiffrin, 2013). Although these paradigms would be difficult to implement with young infants, they could be translated into paradigms suitable for school-aged children.

Across various aspects of language acquisition, researchers have adopted the approach of using children rather than adults as models of infant language learning. In some cases, researchers have found very little difference between adults' and children's performance (Saffran, 2001, 2002; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Others, however, have identified conditions under which adults and children perform differently (Hudson Kam & Newport, 2005, 2009). Finally, some researchers have proposed that the differences between adults and children are mainly quantitative, rather than qualitative, in nature (e.g., Braine et al., 1990; Ferman & Karni, 2010; Janacsek, Fiser, & Nemeth, 2012; Piccin & Waxman, 2007). Thus, although early school-aged children are far from equivalent to novice language learners, their inherently more limited memory and attentional capacities may nonetheless lead to different patterns of performance compared with adult learners. This approach has the potential to inform whether the cross-situational learning findings gleaned from adult learning tasks are relevant for developmental accounts.

A second reason to study word learning in this population is that this is a period of development during which children are very much in the midst of building their vocabulary. In fact, the rate of vocabulary growth during middle childhood is greater than that during late infancy and toddlerhood, the period typically emphasized in word learning research (for discussions, see Anglin, 1993; Bloom, 2000; Snedeker, 2009). Thus, an understanding of cross-situational word learning during this period of vocabulary development has the potential to inform not only the role of cross-situational learning during earlier stages of lexical development but also the constellation of learning processes that support prolific word learning more generally.

In what follows, we present two experiments that investigated cross-situational statistical word learning and its underpinnings in school-aged children. We had two specific goals. First, we investigated whether children's cross-situational word learning is, in fact, cross-situational in nature. Smith and colleagues (2009) recently demonstrated that success in a cross-situational learning paradigm does not necessarily entail aggregating information across situations and that task success could, in some testing conditions, be the product of a single-trial learning strategy. In Experiment 1, we tested whether children's learning actually involved aggregating information across situations by examining the effect of context diversity on children's learning. Contextual diversity is indexed by the number of different sets of stimuli with which each word–object pairing co-occurs across learning trials. Because contextual diversity refers to an aspect of the learning environment that is, by definition, cross-situational in nature, it could affect learning only if children were aggregating information across situations.

The second goal of the current work was to investigate the robustness of the word mappings children form as a function of cross-situational word learning. Toward this end, in Experiment 2 we examined whether children could, following exposure to only a few ambiguous naming events, distinguish a word's referent from other distracter objects that had also co-occurred with the word at varying levels of frequency. The extent to which children can discriminate referents based on fine-grained differences in co-occurrence frequency speaks to the strength of the word-to-referent mappings obtained through cross-situational learning.

Experiment 1

To test cross-situational word learning capacities in school-aged children, we adapted Yu and Smith's (2007) adult cross-situational word learning paradigm to render the task suitable for young children. As in the adult paradigm, children encountered ambiguous naming events in which they saw multiple pictures of objects and heard multiple words with no disambiguating information regarding which word referred to which picture. Across situations, words and their referents always co-occurred together, whereas their accompanying word–referent pairings varied. Thus, the logic behind the paradigm was that children could determine word reference only if they were able to use the cross-situational co-occurrence information.

Although success on this task has generally been interpreted as evidence for cross-situational learning, Smith and colleagues (2009) recently proposed an alternative explanation for success in this task. They argued that a learner who simply remembers a snapshot of a single trial, keeping track of the set of objects present during one presentation of a given word, could still perform above chance on the forced-choice task employed in this paradigm. That is, provided that the set of objects present at test includes only a subset of those present during the sole remembered learning trial, a learner could perform above chance simply by selecting at random from the test pictures that had also been presented during the single encoded learning trial for a particular word.

Given K. Smith and colleagues' critique, coupled with evidence suggesting that, relative to adults, children may be less likely to aggregate information across trials (e.g., Piccin & Waxman, 2007), the current paradigm includes a manipulation that tests whether children employ a single-trial learning strategy versus a truly cross-situational one. Specifically, children participated in one of three learning conditions that differed in the contextual diversity of the learning environment. We defined contextual diversity as the degree of variability in the set of word–object pairings with which a particular word–object pair co-occurs *across* naming events. We argue that if children are more successful at making word–referent mappings with higher context diversity than with lower context diversity (as others have documented in adult learners; see Kachergis et al., 2009; Suanda & Namy, 2012), children must have employed a cross-situational learning strategy. This is because contextual diversity arises across multiple situations, and a single-trial learner would not encode information about variability across multiple situations. In contrast, if we do not observe an effect of contextual diversity in children's learning, we cannot rule out the possibility that children employed a single-trial learning strategy.

Method

Participants

A sample of 84 5- to 7-year-olds (mean age = 73.6 months, range = 57.3–94.9, 49 girls and 35 boys) participated. In terms of race, 77% of children were Caucasian, 19% were African American, 2% were Asian, and 1% were of other racial categories, with 9% of families identifying as Hispanic or Latino. All children were native speakers of English. An additional 13 participants were excluded from data analysis due to exhibiting a position bias (see "Coding" section below).

Stimuli

Stimuli included eight recorded bisyllabic novel words (*tanzer*, *bemkin*, *japple*, *daxen*, *hiplex*, *foppick*, *corwit*, and *renkle*) spoken by the same female speaker using adult-directed speech and neutral (list-like) prosody. Each word was paired with a picture of an uncommon or artificially altered object (see Fig. 1) to create eight to-be-learned word–object pairings. Initial pilot data revealed that children exhibited no bias toward learning any particular word–object mapping. Four additional novel word–object pairings were used for a familiarization phase of the experiment. Stimuli were incorporated into an in-house computer application used to control stimulus presentation on a 17-inch monitor connected to a Power Mac G5. An add-on touch screen was mounted onto the monitor to allow children to advance trials and make selections at test.

Fig. 1. Pictures of novel/altered objects employed in Experiments 1 and 2.

Design

Children were randomly assigned to one of three conditions varying in the contextual diversity of the learning environment: High Contextual Diversity (High CD), Moderate Contextual Diversity (Moderate CD), and Low Contextual Diversity (Low CD). In all three conditions, a word co-occurred with its referent in a total of four trials. In each learning trial, a second word and picture was also presented, with the correspondence between words and pictures being ambiguous on any given trial. Conditions differed in the number of *different* distracters with which a word co-occurred across the four trials as well as the *frequency* with which a given distracter co-occurred with a word. In the High CD condition, for any given word–picture pairing, the accompanying word–picture pair was different on each of the four trials. In the Moderate CD condition, word–picture pairings co-occurred with one word–picture pairing on two trials and two other word–picture pairings on the other two trials, resulting in less diversity across trials. Finally, in the Low CD condition, word–picture pairings co-occurred with one word–picture pairing three times and another word–picture pairing once, so the diversity across trials was low. (For a more detailed depiction of the co-occurrence structure of each condition, see Appendix.)

Procedure

Children sat in front of the touch-screen computer next to the experimenter with a video camera positioned over children's shoulder. The experimenter employed a ladybug puppet named "Lulu the Ladybug" and introduced the experiment as a game with the goal of learning Lulu's names for her favorite toys. Children completed a familiarization phase followed by a learning phase and a test phase. The goal of the familiarization phase was to introduce children to the experimental setting and to the general goal of learning Lulu's names for her toys. This procedure was thoroughly piloted and adapted to optimize task comprehensibility for children. There were three parts to the familiarization phase. First, the 12 pictures (the eight to-be learned pictures and four additional pictures) were displayed simultaneously on the computer screen. Then, the 12 novel words that corresponded to each of the pictures were played in a random order. The experimenter then told children, "We are going to learn which name goes with which picture." In the second step of the familiarization phase, the experimenter explicitly taught children the name of two of the pictures (which were not going to be part of the experiment proper). One of these pictures was presented on the computer screen, and its corresponding word was played. This was repeated for the second picture. Then, children's learning of

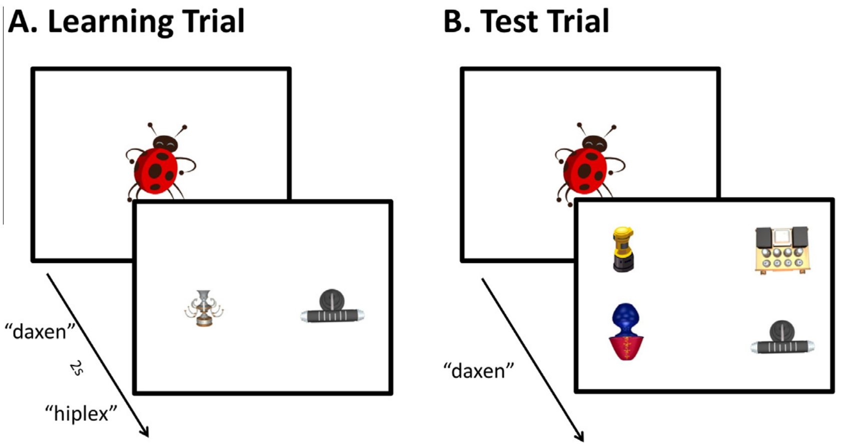

Fig. 2. Sample trial structure in this paradigm: a learning trial (A) and a test trial (B).

those two words was tested in two four-alternative forced-choice (4AFC) trials. In these trials, the same four pictures (the two labeled pictures and two unlabeled pictures) appeared simultaneously on the computer screen. In the first trial, the first novel word was played and children were asked to make a choice by touching the picture they thought went with the word. A second 4AFC trial tested children's learning of the referent of the second novel word. Correct selections were reinforced by the experimenter's clapping and a rewarding audio clip (applause and cheering). For any incorrect selections, children were asked to make a different selection until they were correct. The two novel word–picture pairings taught during the familiarization phase as well as the two distracters present in the 4AFC test trials of the familiarization phase did not appear during the experiment proper. The goal of the familiarization phase was simply to familiarize children with the game of learning words. Given that there was no referential ambiguity in the learning of words during this phase, the familiarization phase was not likely to "train" children on how to learn words cross-situationally. However, it did familiarize children with the experimental setting, the touch screen, the 4AFC task, and the task goal of learning new words.[1]

Following the familiarization phase, children proceeded immediately to the learning phase. At this time, the experimenter said, "Now, we are going to learn all of the names of Lulu's other toys." In each trial of the learning phase, children saw two pictures, one on each side of the monitor. Children also heard two spoken words, played sequentially in random order, corresponding to the two pictures (see Fig. 2A).

Each of the eight to-be-learned word–object pairings occurred on four trials throughout the learning phase. Given that these 32 instances of word–object pairings were presented two at a time on each trial, the learning phase consisted of 16 total learning trials. Two training lists were created with the order of the trials pseudo-randomized such that each of the eight word–object pairings appeared once before any given pairing was repeated and no word–object pairing appeared in back-to-back trials, consistent with Yu and Smith's original adult paradigm. The training list used was counterbalanced across participants.

The test phase immediately followed the learning phase and consisted of eight 4AFC test trials, one per target word. In each trial, four pictures appeared simultaneously, one in each quadrant, followed by the presentation of the target word (see Fig. 2B). Children indicated which picture they thought went with the target word by touching the picture on the screen. Children received no feedback during

[1] This familiarization procedure constitutes a departure from Yu & Smith's, 2007 adult paradigm. Given previous work suggesting that pre-exposure to objects improves word learning in 2-year-olds Kucker and Samuelson (2012), it is possible that this procedure had similar effects on 5- to 7-year-old learners. Importantly for the current contexts, however, there is no reason to suspect that the familiarization procedure would differentially affect some conditions of contextual diversity more than others.

the test phase. All test trials were constructed by selecting the target word's corresponding picture and three foils randomly selected from the set of objects that had never co-occurred with the target word during the learning phase. All pictures served as foils an equal number of times. Two test lists were created and were identical across conditions. The test list employed was counterbalanced across participants.

Because none of the foils co-occurred with the target word during the learning phase, this testing regimen was not designed to detect whether children definitively mapped the target word to its correct referent. Instead, this procedure simply tested children's sensitivity to whether the word had co-occurred with the target picture at all during the learning phase. Although this testing regimen did not provide the most rigorous test of word mapping *within* each condition, it did provide a straightforward way to assess the effect of contextual diversity *across* conditions while keeping the structure of the test trials constant.

Coding

For each test trial, children's choices were automatically registered as correct or incorrect. Children were classified as exhibiting a position bias and excluded from the analysis if they selected the object located in the same quadrant on five or more of the eight trials, which is the point at which, through a binomial test, the probability of selecting a single quadrant across eight independent trials is statistically greater ($p < .05$) than would be predicted by chance responding.

Results

For each child, we computed the proportion of test trials answered correctly. We then derived a mean proportion correct for each contextual diversity condition. Initial analyses (2×2 analyses of variance [ANOVAs]) within each condition revealed no effects of training list, testing list, or interaction (smallest $p = .09$)[2] on mean proportion correct. Thus, all subsequent analyses were collapsed across training and testing lists. There were also no sex differences in performance, $t(82) = -1.03$, $p = .30$, and no correlation between age and mean proportion correct, $r(82) = .09$, $p = .43$.

Fig. 3 shows the mean proportion correct across conditions of contextual diversity ($M_{High} = .48$, $SD = .21$; $M_{Mod} = .39$, $SD = .20$; and $M_{Low} = .34$, $SD = .18$). To test whether children demonstrated word learning, for each condition we conducted single-sample *t* tests to examine whether mean proportion correct was above the proportion that would be expected from chance performance (.25) in each condition. These tests revealed that learning was significantly higher than chance performance in all three conditions, $t_{High}(27) = 5.80$, $d = 1.10$; $t_{Mod}(27) = 3.57$, $d = 0.67$; and $t_{Low}(27) = 2.77$, $d = 0.52$, all $ps < .01$. This finding underscores the power of children's cross-situational learning: from only a handful of ambiguous naming events, children mapped words to their referents even when confronted with low levels of contextual diversity.

To investigate the effect of contextual diversity on learning, we conducted a one-way ANOVA on mean proportion correct with condition as a between-participants factor. As depicted by the downward trend in mean proportion correct across conditions in Fig. 3, contextual diversity had a significant effect on performance, $F(2,81) = 3.53$, $p = .03$, $\eta^2 = .08$. Planned comparisons with Bonferroni correction revealed that the only statistically significant pairwise difference was between the High CD and Low CD conditions, $t(54) = 2.64$, $p = .03$. The difference between the High CD and Moderate CD conditions, $t(54) = 1.68$, $p = .25$, or between the Moderate CD and Low CD conditions, $t(54) = 0.87$, $p = 1.00$, did not reach statistical significance. The finding that increased contextual diversity improves cross-situational word learning is consistent with research with adult learners in a similar paradigm (Kachergis et al., 2009; Suanda & Namy, 2012).

To investigate how representative these group-level results were of individual children's performance, we examined individual patterns of performance, dichotomizing children in each condition as either performing numerically above chance or performing at/below chance (.25). Fig. 4 illustrates

[2] This was observed in a test of the training list effect in the Moderate CD condition, $F(1,24) = 3.154$, $p = .09$. All other preliminary analyses had *p* values greater than .25.

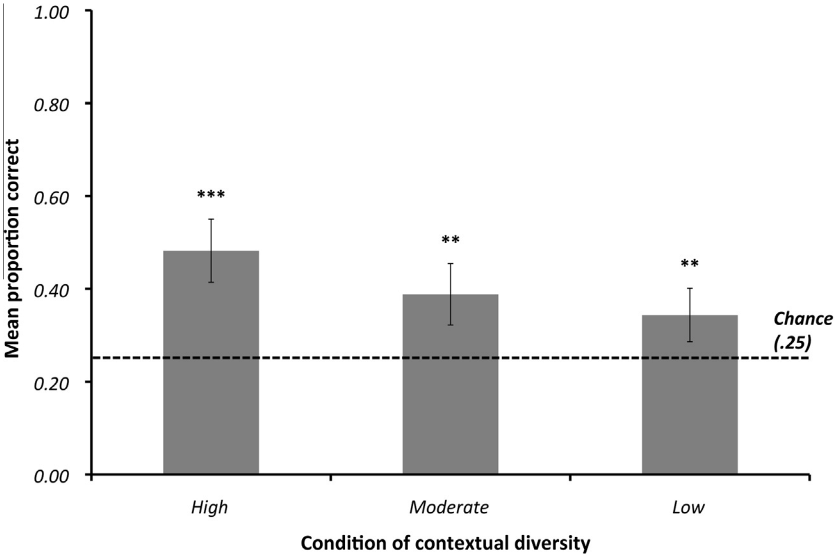

Fig. 3. Mean proportions correct across levels of contextual diversity. **$p < .01$; ***$p < .001$. Error bars reflect 95% confidence intervals around the means.

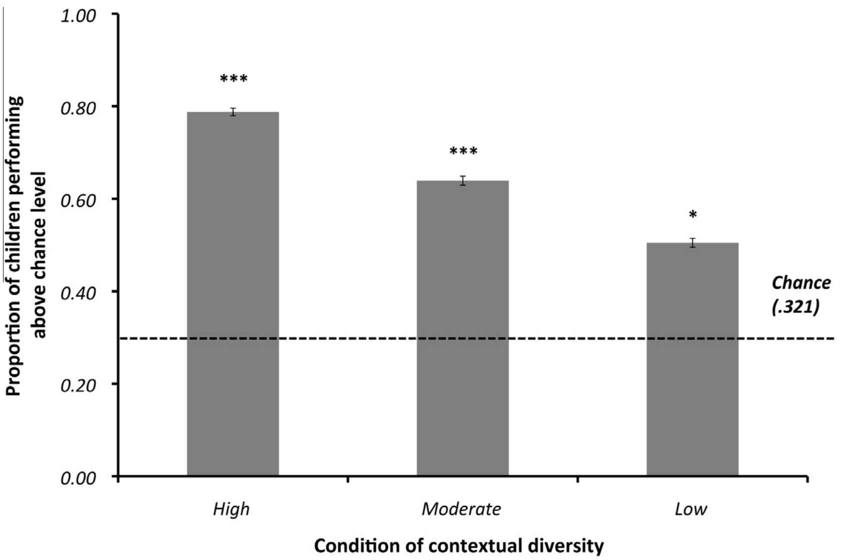

Fig. 4. Proportions of children performing above chance across levels of contextual diversity. *$p < .05$; ***$p < .001$. Variability estimates of the data were obtained via 200 iterations of bootstrap resampling. Error bars reflect 95% confidence intervals around the observed data.

the proportions of children across conditions who performed above chance level. The main patterns of the group-level analyses were upheld at the individual level. That is, chi-square goodness-of-fit tests revealed that the proportion of children performing above chance in each condition ($Prop_{\mathrm{High}} = .786$, $Prop_{\mathrm{Mod}} = .643$, and $Prop_{\mathrm{Low}} = .500$) was statistically greater than the proportion that would be predicted from chance performance (.321),[3] $\chi^2_{High} = 27.74$, $p < .001$; $\chi^2_{Mod} = 13.31$, $p < .001$; and $\chi^2_{Low} = 4.12$, $p = .04$. Furthermore, a chi-square test of independence revealed a marginally significant effect of contextual diversity condition on the distribution of individual performance, $\chi^2 = 4.97$, $p = .08$. Fig. 4 illustrates that the higher the contextual diversity of the learning environment, the greater the proportion of children who performed above chance.

Discussion

In the current experiment, 6-year-old children learned word-to-referent mappings from just a handful of ambiguous naming events, suggesting developmental continuity in cross-situational word learning mechanisms across infancy, childhood, and adulthood. Although children demonstrated learning across all conditions of contextual diversity, children's learning patterns clearly indicated that the more diverse the learning contexts, the better the learning. These findings are consistent with previous work suggesting that infants, toddlers, and adults are prodigious cross-situational word learners (Scott & Fisher, 2012; Smith & Yu, 2008; Yu & Smith, 2007) and that contextual diversity influences performance in adult learners (Kachergis et al., 2009; Suanda & Namy, 2012). The contextual diversity effect sheds light on the underlying learning strategy children employed in this task. Although the specific mechanism remains unclear, the fact that contextual diversity affects learning rules out a single-trial learning strategy (Smith et al., 2009) as a candidate process and suggests that the process is one that involves combining co-occurrence information across situations.

The finding that greater diversity in learning contexts aided children's word-to-referent mapping is also consistent with evidence of college students' word learning from written texts (Bolger, Balass, Landen, & Perfetti, 2008) and observational and corpus analyses that connect early language environments to acquisition outcomes (Hills, Maouene, Riordan, & Smith, 2010; Hoff & Naigles, 2002). Furthermore, this finding is in accord with a broader body of evidence suggesting that increasing variability of learning environments improves learning (Gomez, 2002; Hintzman & Stern, 1978; Postman & Knecht, 1983; Rost & McMurray, 2009, 2010; Smith, Glenberg, & Bjork, 1978; Verkoeijen, Pikers, & Schmidt, 2004).

Although there is abundant evidence demonstrating *that* contextual diversity helps learning, the precise *reason* for why it helps is unclear. At least three hypotheses have been put forward. First, some have argued that increasing variability of learning instances allows for more decontextualized representations (e.g., Apfelbaum & McMurray, 2011). Second, based on earlier memory research, some scholars have argued that contextually diverse learning environments allow for a greater number of potential cues at time of memory retrieval (Bower, 1972; Glenberg, 1979). Finally, Bjork and colleagues have offered an explanation based on the notion of "desirable difficulties" in learning. That is, contextually diverse learning opportunities initially create more difficult individual learning instances due to the mismatch between learning instances. This initial difficulty boosts the strength of learning in the long run so long as the encoding of individual instances is successful (Bjork, 2011). Thus, a number of potential explanations exist to explain the current findings.

Adding to the puzzle of the basis for contextual diversity effects in learning is the large number of findings across the memory, learning, and language literatures that fail to find a benefit of contextual diversity on learning (Dempster, 1987; Postman & Knecht, 1983; Young & Bellezza, 1982) as well as those that find a benefit for context *redundancy* on learning outcomes (e.g., Benitez & Smith, 2012; Haryu, Imai, & Okada, 2011; Maguire, Hirsh-Pasek, Golinkoff, & Brandone, 2008; Vlach & Sandhofer, 2011). For example, in one study of early verb learning, Maguire and colleagues (2008) presented 2-year-olds with an actor performing a novel action coupled with a verb-naming event, "Wow, watch her *blicking*!". The 2-year-olds either saw four instances of the same actor *blicking* or saw four

[3] Chance for this analysis was defined as the proportion of times one would expect to see a participant perform above chance (.25) if participants randomly guessed on each trial. This chance value was derived from multiplying the likelihood of each response pattern given random guessing (i.e., the likelihood of getting exactly three trials correct, four trials correct, etc.) and the number of permutations of each response pattern that is above chance (e.g., there are exactly 56 different ways in which a random performer would get exactly three trials correct: Trials 1, 2, and 3 are correct, Trials 1, 2, and 4 are correct, Trials 1, 2, and 5 are correct, etc.).

instances of four different actors *blicking*. Maguire and colleagues found that children who were presented with the same actor on all learning instances were better able to extend the label to a novel instance of *blicking* (i.e., with a novel actor). Thus, although the current findings (see also Kachergis et al., 2009; Suanda & Namy, 2012) clearly demonstrate a positive effect of increased contextual diversity in cross-situational word learning, how they relate to other findings of contextual diversity is a topic for future research.

Experiment 2

Although the results of Experiment 1 demonstrated successful cross-situational word learning, they did not address the strength of the mappings children made from these few ambiguous naming events. Recall that the structure of the test trials in Experiment 1 involved the presentation of a target word, a target object, and three foil objects that had *never* occurred with the target word during the learning phase. Although this structure allowed for equating the structure of the test trials across conditions and, thus, served as a conservative test of the effects of contextual diversity on learning, the test structure can only tell us whether participants had built up some level of word-to-referent association; it does not address the relative strength of this association. In the second experiment, we replicated the Moderate CD condition from Experiment 1 using a more stringent measure of word–referent mapping. Specifically, we examined whether children can determine a word's correct referent from among an array of foils that had also co-occurred with the target word with varying frequency during learning.

Method

Participants

A sample of 28 5- to 7-year-olds (mean age = 74.7 months, range = 62.5–96.5, 14 girls and 14 boys) participated. In terms of race, 78% of children were Caucasian, 13% were African American, 3% were Asian, and 6% identified as members of other racial categories, with 6% of families identifying as Hispanic or Latino. All children were native speakers of English.

Stimuli, design, and procedure

The stimuli, design, procedure, and coding were identical to those in Experiment 1 with the following exceptions. First, there was only one learning condition in this experiment. The contextual diversity of the learning environment was identical to that of the Moderate CD condition of Experiment 1 (see Appendix). The critical difference between Experiments 1 and 2 was the structure of the test trials. In Experiment 1, the foils presented on test trials had never co-occurred with the target word during learning. In Experiment 2, the foils *had* co-occurred with the target word during learning. Specifically, each of the eight 4AFC test trials was constructed such that the target referent for each word was paired with three pseudo-randomly selected foils that included one foil that had co-occurred with the target word on two of the four learning trials, one foil that had co-occurred with the target word once during the learning phase, and a third foil that had never co-occurred with the target word during the learning phase. We were interested in whether children would demonstrate cross-situational word learning under these more difficult test conditions. We were also interested, when children made errors, in whether children were more likely to select foils that had co-occurred most often during learning. This speaks to the precision with which children learned word–referent pairings across learning events.

Results and discussion

As in Experiment 1, we computed the proportion of trials each child answered correctly. Preliminary analyses revealed a significant effect of training list, $F(1,24) = 4.56$, $p = .043$, qualified by a significant interaction between training list and test list on mean proportion correct, $F(1,24) = 4.56$, $p = .043$, indicating that performance in one training–test list combination was significantly higher than the others. An inspection of the data revealed that this effect was driven primarily by a single child who performed well above the group mean. When this child was removed from the analysis, the training and testing list effect was no longer statistically significant, $F(1,23) = 3.28$, $p = .08$. Importantly, the statistical significance of the primary analyses presented below was not markedly altered when this participant's data were removed from analyses. As in Experiment 1, we found no correlation between age and performance, $r(26) = -.01$, $p = .97$, and no sex differences in performance, $t(26) = -0.37$, $p = .71$.

To examine the extent to which participants learned word-to-referent pairings in this more challenging testing regimen, we performed a single-sample t test on mean proportion correct against the learning rate that would be expected by chance performance (.25). Results revealed that the mean proportion correct ($M = .335$, $SD = .19$) was significantly higher than chance level, $t(27) = 2.41$, $p = .02$, $d = 0.45$, suggesting that children successfully mapped words onto their referents. This group-level analysis was supported by an individual-level analysis of performance. A chi-square goodness-of-fit test revealed that the proportion of children performing above chance was significantly higher than what would be predicted by random performance, $\chi^2 = 4.12$, $p = .04$.

To examine the effects of the testing environment on performance, we conducted an independent samples t test comparing performance in Experiment 2 with that in the Moderate CD condition of Experiment 1. Results revealed that although the difference between the two samples was in the expected direction (i.e., performance in Experiment 2 where co-occurring foils were present at test was lower, $M_{\text{Exp 2}} = .33$; $M_{\text{Exp 1–Mod CD}} = .39$), the difference was not statistically significant, $t(54) = 1.02$, $p = .31$.

We also examined the nature of children's response patterns, investigating the extent to which the item selected on each trial reflected the co-occurrence frequency between the target word and each of the four pictures in that trial. That is, were children more likely to select objects that co-occurred more frequently with the target word than to select objects that co-occurred less frequently with the target word? Fig. 5 illustrates the relation between the likelihood of selecting a particular picture and the

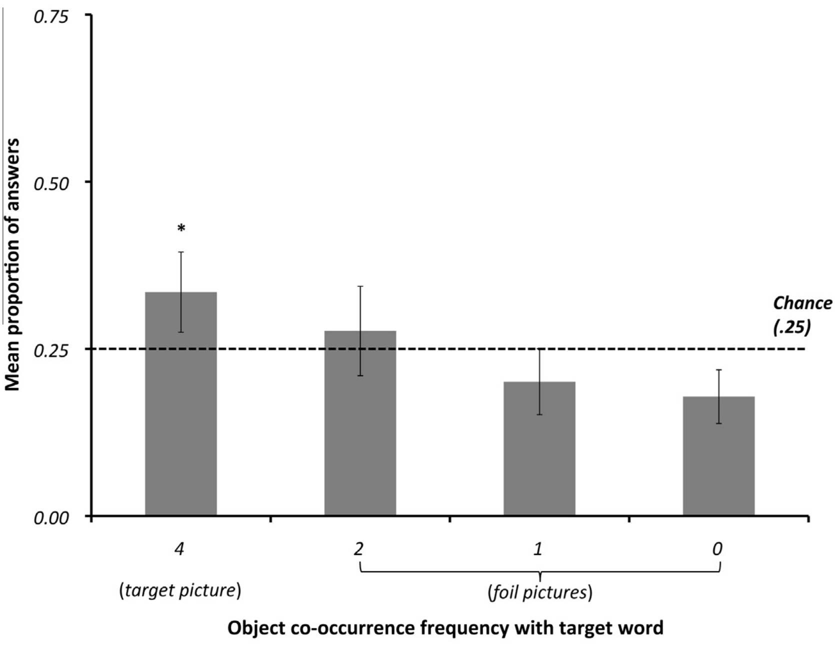

Fig. 5. Distribution of answers to objects differing in co-occurrence frequency with target word. Error bars reflect 95% confidence intervals around the means.

word-to-picture co-occurrence frequency. As the figure shows, there is a clear relation between frequency of co-occurrence and item selection; the more frequently a word and picture co-occurred during learning, the more often that picture was selected at test. These findings suggest that, as in previous research with adult learners (Suanda & Namy, 2012; Vouloumanos, 2008), children's mappings reflect the statistical structure of the learning environment. The figure also illustrates that although children selected the target picture more often than predicted by chance, on average, children were almost as likely to select the closest co-occurring competitor as they were to select the target picture. Indeed, when we considered only selections to the target picture and the high-frequency co-occurring competitor (61% of all selections), children did not select the target picture ($M = .56$, $SD = .28$) more often than what would be predicted by chance (.50), $t(27) = 1.19$, $p = .24$. These findings suggest that although children were able to use relative frequency of co-occurrence with the target word as a basis for responding, there appeared to be imprecision in children's mappings.

There are two mapping patterns that could result in the imprecision we observed. First, children may have mapped some target words to the correct and most frequently co-occurring picture but incorrectly mapped other words to the most frequently co-occurring foil. Alternatively, children may have associated target words (either explicitly or implicitly) with *both* the target picture and the frequently co-occurring foil. In such a case, these results would reflect the fact that children could not consistently discriminate between the target word's associative strength and the two different pictures. Based on the current data, we cannot distinguish between these two possibilities. We discuss the mechanistic issues raised by this particular finding in greater detail below.

General discussion

In the current study, we investigated the extent to which young children could learn word-to-referent mappings from a small number of naming events involving ambiguous reference. The results of two experiments suggest that children, like infant learners (Smith & Yu, 2008, 2013) and adult learners (Yu & Smith, 2007), can learn words when the only clues to reference are the cross-situational word-to-reference co-occurrence statistics. The findings from Experiment 1 revealed that children's learning, like adults' learning (see Kachergis et al., 2009; Suanda & Namy, 2012), is affected by the contextual diversity of the learning environment. The findings from Experiment 2 revealed the robustness of children's cross-situational word learning and suggested that children, like adults (see Suanda & Namy, 2012; Vouloumanos, 2008), exhibited response patterns that reflected the co-occurrence statistics of the learning environment.

Much of the developmental research on cross-situational word learning has focused on infant and toddler populations (Akhtar & Montague, 1999; Scott & Fisher, 2012; Smith & Yu, 2008, 2013; Yu & Smith, 2011; but see Piccin & Waxman, 2007, and Werner & Kaplan, 1950, for notable exceptions). This focus on young word learners is warranted; to the extent that cross-situational word learning is a viable candidate process that gets word learning off the ground, it is important to demonstrate the availability of this learning process in the youngest of word learners. But what about the role of cross-situational word learning in later vocabulary development? The current results highlight the availability of a powerful statistical word learning capacity in children and, thus, suggest the possibility that cross-situational learning may play an important role in word learning across development. Of course, just because children can exploit the co-occurrence statistics in the service of word learning in the current task, it does not mean that children deploy this capacity in their everyday word learning. Interestingly, however, there is some evidence from the education and reading studies literatures that suggest the potential use for a cross-situational word learning mechanism during middle childhood as well as early childhood. That is, many words learned during this phase of development are acquired unintentionally in reading contexts (Gordon, Schumm, Coffland, & Doucette, 1992; Nagy, Anderson, & Herman, 1987; Nagy, Herman, & Anderson, 1985; Shu, Anderson, & Zhang, 1995) or listening contexts (Elley, 1989; Robbins & Ehri, 1994). Research on this type of word learning, known as *incidental word learning* (Nagy et al., 1985), suggests that in these contexts children benefit from multiple exposures to words and that a single exposure is rarely sufficient for learning (Horst, Parsons, & Bryan, 2011; Jenkins, Stein, & Wysocki, 1984; Robbins & Ehri, 1994). Further research is needed to investigate the extent to which findings such as these on school-aged children's vocabulary acquisition are linked to the types of processes that underlie the cross-situational learning reported in the current study. This step is of particular importance considering that children's real-world learning environments are substantially more complex than the learning environments presented in artificial laboratory tasks such as the ones described here.

The fact that children's learning in the current study showed similar patterns to adults' learning in previous work—both are sensitive to contextual diversity (see Kachergis et al., 2009; Suanda & Namy, 2012), and both show response patterns that reflect the statistics in the input (see Suanda & Namy, 2012; Vouloumanos, 2008)—suggests continuity across development in the underlying mechanisms of cross-situational word learning. This finding is in accord with a number of statistical language learning studies in other aspects of language acquisition, such as speech segmentation (Saffran et al., 1997) and sequence learning (Meulemans, Van der Linden, & Perruchet, 1998), that also find similarities between adults' and children's statistical learning. This does not imply, of course, that child learning patterns consistently conform to adult patterns across all aspects of language acquisition. Indeed, one hallmark of language in general is that it is more readily (and therefore differently) acquired by children than by adults. For example, in their work on grammar regularization, Hudson Kam and Newport (2005, 2009) found that adults and children exhibit different patterns in their regularization of a probabilistic determiner system, with children more likely to regularize than their adult counterparts.

Of course, even when researchers do find behavioral similarities between adult and child learners, as we did here, it is not a given that they are driven by the same underlying processes. This issue is particularly pertinent in the context of cross-situational word learning given that researchers have argued and demonstrated computationally that multiple mechanisms can readily account for many of the existing cross-situational learning findings (see Trueswell et al., 2013; Smith et al., 2011; Yu & Smith, 2012). More specifically, the capacity to capitalize on cross-situational regularities in word learning can be explained by two distinct computational processes. According to an associative learning account of cross-situational learning, when children encounter a new word in an ambiguous naming event, they encode the connection between this word and multiple, if not all, co-occurring objects. As children encounter this word in subsequent naming events, they strengthen previous connections as well as create new connections. This process of aggregating cross-situational co-occurrence statistics yields successful learning because, on average, the associations between words and their referents will be stronger than incorrect mappings based on frequency of word–object co-occurrence (Yu, 2008; Yu & Smith, 2012).

Alternatively, according to a hypothesis testing account of learning, cross-situational word learning occurs because children pick out a specific object as a hypothesized referent of the word when they encounter a new word in an ambiguous naming event. As children encounter this word in a subsequent naming event, they either confirm the hypothesis if it is consistent with the event (i.e., the initially hypothesized referent is also present in the subsequent event) or reject and replace the hypothesis if it is inconsistent with the event (i.e., the initially hypothesized referent is not present in the subsequent event). This process of confirming or replacing hypothesized word-to-referent mappings should yield successful cross-situational word learning based on the logic of probability; more frequently co-occurring word-to-object pairs will be more likely selected as word-to-referent hypotheses than infrequently co-occurring word-to-object pairs (see Medina et al., 2011; Trueswell et al., 2013).

The current studies, modeled after the original adult paradigm (Yu & Smith, 2007), do not speak to which of these accounts best characterizes children's learning. In a thoughtful discussion of these two accounts, Yu and Smith (2012) argued that distinguishing between them is not straightforward and that deciding which characterizes learning might not be a productive route to understanding the phenomenon. This is because each of these accounts can be decomposed into several processes (e.g., the amount of information learners select from the environment and the nature of the information retrieved from memory) and because, depending on the configuration of the proposed processes, one account may look indistinguishable from the other (see also L. Smith, Suanda, & Yu, 2014).

Recent empirical work with adult learners also supports the rejection of a simple either/or approach to understanding cross-situational word learning. Smith and colleagues (2011), for example, revealed that adults' cross-situational learning strategies shift as a function of the nature of the learning task (specifically the degree of referential uncertainty). That is, when referential uncertainty is low, learning approximates associative learning; when referential uncertainty is high, learning approximates hypothesis testing. In addition, Romberg and Yu (2014) demonstrated, using a learning paradigm that encourages learners to engage in both hypothesis testing and associative learning (arguably a better model of real-world word learning), that there is mutual influence between testing hypotheses and aggregating associations. These recent studies, thus, underscore the likely complex interplay of multiple mechanisms behind cross-situational word learning. Future modifications to our current paradigm (e.g., varying task difficulty or adopting a continuous learning paradigm) should help to shed light on what cocktail of mechanisms underlie *children's* cross-situational word learning.

In conclusion, the current results provide the first empirical evidence that school-aged children can learn word-to-referent mappings across multiple ambiguous naming events. These results suggest statistical word learning as a candidate learning mechanism for later phases of vocabulary acquisition as well as earlier ones. The current endeavor not only demonstrates that children *can* learn words cross-situationally but also provides important evidence regarding developmental consistency in the learning mechanism by demonstrating that some of the same factors previously shown to influence adults' learning also influence children's learning.

Acknowledgments

We thank all the families who volunteered to make this research possible. We thank Lynne Nygaard, Rob Hampton, Phil Wolff, and Stella Lourenco for helpful comments on this project. We also thank Maggie Dancel, Pat Finan, Ann Marie Finley, Arielle Friehling, Katie Kimura, and Carlie Marks for their assistance with subject recruitment and coding. A portion of the stimulus images used is courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, http://www.tarrlab.org/. This research was part of the first author's doctoral dissertation submitted to Emory University and portions of this research were presented at the Biennial Meeting of the Society for Research in Child Development, 2011, and the Biennial Meeting of the Cognitive Development Society, 2011. This research was supported by an NSF GRF awarded to SHS, by SIRE grants from Emory College awarded to NM and LLN, and in part by NICHD grant number 5-R03-HD058777-02 awarded to LLN. The material in this article is based in part on work done while the third author was employed as a National Science Foundation Program Director. Any opinion, findings, and conclusions expressed in this article are those of the authors and do not necessarily reflect the views of the U.S. National Science Foundation.

Appendix

Association Matrices representing word – picture co-occurrence frequencies across conditions

A. High CD

		Words							
		1	2	3	4	5	6	7	8
Pictures	1	4	1	1	1	1			
	2	1	4	1	1		1		
	3	1	1	4	1			1	
	4	1	1	1	4				1
	5	1				4	1	1	1
	6		1			1	4	1	1
	7			1		1	1	4	1
	8				1	1	1	1	4

B. Moderate CD

		Words							
		1	2	3	4	5	6	7	8
Pictures	1	4	2	1	1				
	2	2	4	1	1				
	3	1	1	4	2				
	4	1	1	2	4				
	5					4	2	1	1
	6					2	4	1	1
	7					1	1	4	2
	8					1	1	2	4

C. Low CD

		Words							
		1	2	3	4	5	6	7	8
Pictures	1	4	3	1					
	2	3	4		1				
	3	1		4	3				
	4		1	3	4				
	5					4	3	1	
	6					3	4		1
	7					1		4	3
	8						1	3	4

The above table illustrates the total frequencies with which words (columns) co-occurred with different pictures (rows) in each condition. To illustrate co-occurrence patterns in the High CD condition, Word 1 (W1) co-occurred with its referent (Picture 1 – P1) on all four trials in which W1 occurred.

W1–P1 was accompanied by W2–P2 on one of those trials, W3–P3 on a different trial, W4–P4 on another trial, and W5–P5 on yet another trial, resulting in maximal contextual diversity.

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