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Brief article

Memory constraints on infants' cross-situational statistical learning

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ABSTRACT

Infants are able to map linguistic labels to referents in the world by tracking co-occurrence probabilities across learning events, a behavior often termed *cross-situational statistical learning*. This study builds upon existing research by examining infants' developing ability to aggregate and retrieve word-referent pairings over time. 16- and 20-month-old infants ($N = 32$) were presented with a cross-situational statistical learning task in which half of the object-label pairings were presented in immediate succession (massed) and half were distributed across time (interleaved). Results revealed striking developmental differences in word mapping performance; infants in both age groups were able to learn pairings presented in immediate succession, but only 20-month-old infants were able to correctly infer pairings distributed over time. This work reveals significant constraints on infants' ability to aggregate and retrieve object-label pairings across time and challenges theories of cross-situational statistical learning that rest on retrieval processes as successful and automatic.

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1. Introduction

Word learning is often described as a difficult task because the world offers infants a seemingly infinite number of word-to-world mappings in just one moment in time (Quine, 1960). Historically, researchers have examined the constraints learners use to reduce the possible number of mappings in a single moment. The results of this work have suggested that young learners may use several constraints to reduce ambiguity, such as social/cultural (e.g., Tomasello, 1992), representational (e.g., Merriman & Bowman, 1989), and attentional (e.g., Smith, 2000) constraints.

More recent research on word learning has demonstrated that learners reduce ambiguity by detecting and retaining associations across moments in time in a process often termed *cross-situational statistical learning* (Frank, Goodman, & Tenenbaum, 2009; Kachergis, Yu, & Shiffrin, 2012; Onnis, Edelman, & Waterfall, 2011; Siskind, 1996; Smith, Smith, & Blythe, 2010; Smith & Yu, 2008; Vouloumanos & Werker, 2009; Yu & Smith, 2011, 2012; Yurovsky, Boyer, Smith, & Yu, 2013; Suanda & Namy, 2012). That is, learners acquire potential word-to-referent associations across learning events and use this information to guide subsequent inference of word meaning. For example, Smith and Yu (2008) used a preferential looking paradigm to examine cross-situational word learning in 12- and 14-month-olds. Infants were presented with two objects and two words in each learning trial such that it was ambiguous as to which word went with which object. However, across the learning trials, the same word co-occurred with one object. Following the learning trials, infants looked significantly longer at the object that co-occurred with a word (compared to a distractor object) as the word was repeatedly presented to the infant. This work suggests that young infants are able to track co-occurrence probabilities in order to map words to referents in the world.

The majority of research on cross-situational statistical learning has focused on adults' learning and/or mathematical models of learning, rather than infants' learning (see

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Smith & Yu, in press; Vouloumanos & Werker, 2009; Yu & Smith, 2011; Yurovsky et al., in press; for recent exceptions). Although some learning processes may operate in a similar manner across the lifespan, it may be the case that the developmental state of the learner mediates many of these learning processes (Bulf, Johnson, & Valenza, 2011). Thus, the current study examines infants' cross-situational statistical learning in order to expand this body of work and examine potential differences across development.

In particular, the current work extends research on infants' cross-situational statistical learning by examining the developing ability to learn and retrieve word-referent pairings over time in order to later infer word mappings. Young learners need to recall the past both during learning and when making subsequent inferences, yet little is known about how they aggregate past and present associations between words and objects, and how these processes of aggregation may develop in infancy. In real-world learning scenarios, there are likely to be frequent temporal gaps between learning events in which word-referent pairings are encoded. Indeed, retrieving prior word-referent pairings over time is a critical process in several theories of cross-situational learning (for a review, see Yu & Smith, 2012). Thus, a complete theory of cross-situational word learning will have to account for how young infants are able to complete this task.

In the current study, we examined 16- and 20-month-olds' ability to learn word mappings via cross-situational statistical learning. We examined word learning in this developmental period for several reasons. First, previous research has indicated that infants learn cross-situational statistics with object-label pairings presented close together in time as early as 12 months (e.g., Smith & Yu, 2008). Thus, infants at 16 and 20 months should be able to learn the pairings presented in immediate succession. Second, this age span is marked by striking differences in language production and development (pre- vs. post-vocabulary boom; Fenson et al., 1994). Consequently, we predicted that these age groups might also be marked by developmental changes in the ability to learn cross-situational statistics.

Infants were presented with word-referent pairings on two time scales; half of the pairings were presented in learning trials that occurred in immediate succession (massed) and half of the pairings were presented in learning trials distributed across time (interleaved). These presentation conditions provided a direct examination of the developing ability to learning cross-situational statistics over varying timescales.

2. Method

2.1. Participants

Two groups of infants, 16 16-month-old infants ($M = 16.1$ months; range: 15.4–16.4 months; nine girls) and 16 20-month-old infants ($M = 20.2$ months; range: 19.6–20.6 months; nine girls), participated in the cross-situational word learning task. An additional seven infants participated but were excluded because of fussiness/inability to complete the experiment ($N = 4$) or technical/experimenter error ($N = 3$). All children were monolingual English speakers and recruited from a university child participant database. In order to determine children's productive vocabulary, parents completed the MacArthur Bates Communicative Development Inventory: Words and Sentences (MCDI) (Fenson et al., 1994). Infants' productive vocabularies were consistent with developmental norms for both the 16-month-old infants ($M = 81.1$ words, percentile range: 15–99) and 20-month-old infants ($M = 210.5$ words, percentile range: 15–99).

2.2. Apparatus and stimuli

The experiment was presented to infants on a Tobii T60XL eye tracker. The experiment was implemented with Tobii Studio software. The dependent variable was looking at the two objects on the monitor during learning and test trials, operationalized as dwell times (accumulated fixations) in the left or right half of the screen where objects were in view. During all learning and testing trials, the objects were presented on the monitor and the words were presented with the eye tracker's speakers. Infants were seated on a parent's lap ~60 cm from the monitor.

The cross-situational word learning task consisted of a learning phase and a testing phase. During the learning phase, infants were presented with 36 learning trials (trial duration: 4 s) and 12 attention getter trials (a small object moving in tandem with a repetitive non-linguistic sound; trial duration: 3 s). As seen in Fig. 1, each learning trial consisted of two novel objects presented side-by-side on the monitor. The objects were pictures of 3D novel objects used in previous studies of children's word learning (e.g., Vlach, Ankowski, & Sandhofer, 2012) and were controlled for discriminability using adult report. The two objects remained on the screen for the entire duration of each learning trial.

Each learning trial also consisted of two novel linguistic labels, following the phonotactic probabilities of English (e.g., 'blicket' and 'toma') played over the speakers. Each of the two words was played once, using one woman's voice, in random order, for 1 s. The presentation timing of the words was controlled across all of the learning trials; there was a silent onset (.5 s), the presentation of the first word (1 s), a silence between the two words (1 s), the presentation of the second word (1 s), and a silent end to the trial (.5 s). There were a total of 12 linguistic labels and 12 novel objects presented during the learning phase, which were randomly assigned into 12 novel object-novel label pairings. That is, each time that an object was presented during learning, the corresponding linguistic label always co-occurred. The object-label 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 (see Fig. 1). In this design, six of the object-label pairings were randomly assigned to be presented on a massed schedule and six were randomly assigned to be presented on an interleaved schedule. Massed object-label pairings were presented on consecutive learning trials, for

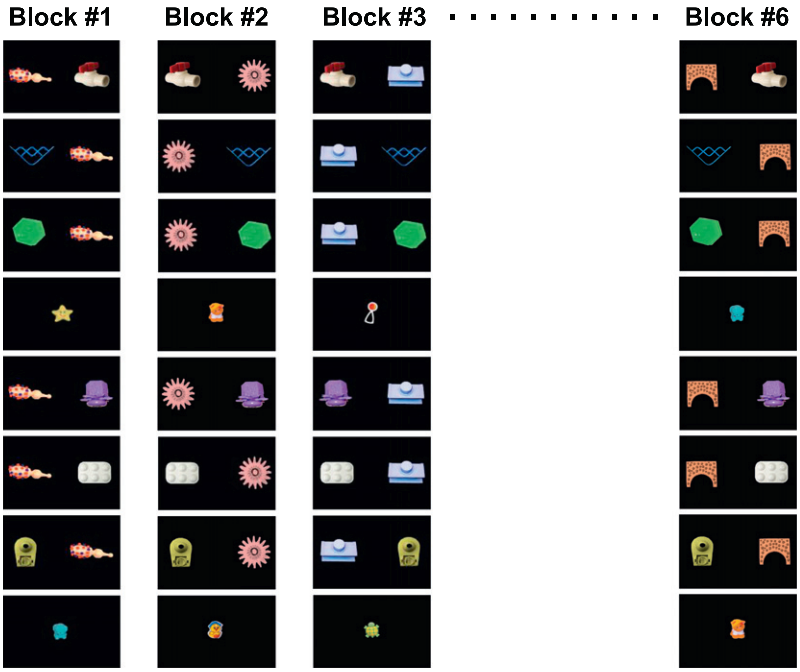

Fig. 1. An example of the learning phase of the experiment. Infants were presented with six blocks of learning, which occurred in immediate succession until all six blocks were presented. Half of the object-label pairings were presented on a massed schedule and the other half-were presented on an interleaved schedule. The massed pairings were presented in immediate succession, in the same block. The interleaved pairings were presented at the same position in each block (for example, always presented on the first learning trial of a block). This design ensured that each interleaved pairing was presented an equal number of times and with an equal amount of time between presentations. An attention getter trial was presented after every three learning trials.

six trials. Interleaved object-label 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 object-label pairings were presented an equal number of times (six presentations) and had an equal amount of time between each of the presentations (26 s).

During the testing phase, there were a total of 12 testing trials (trial duration: 8 s) and 12 attention getter trials (duration: 3 s). An attention getter trial was presented in between each of the testing to re-center infants' attention in between testing trials. Each of the 12 testing trials consisted of two novel objects on the monitor's screen, the target object and the foil object. Additionally, a novel word, which corresponded to the target object, was played over the speakers four times in the same voice used during the learning phase. The presentation timing of the word was controlled across all of the learning trials; there was a silent onset (.5 s), the first presentation of the word (1 s), a silence (1 s), the second presentation of the word (1 s), a silence (1 s), the third presentation of the word (1 s), a silence (1 s), the fourth presentation of the word (1 s), and a silent end to the trial (.5 s). This testing procedure is consistent with prior studies of infants' cross-situational learning (e.g., Smith & Yu, 2008).

Each of the 12 object-label pairings was tested once during the testing phase. Each object-label pairing also served as a foil, the distractor object presented at test, once during testing. The tested objects and foils objects were counterbalanced in order to minimize potential performance differences as a result from the foil presented during the testing trial. For example, for the massed pairing testing trials, half of the foil objects were other massed objects and half were interleaved objects. Conversely, for the interleaved pairing testing trials, half of the foil objects were other interleaved objects and half were massed objects. Finally, the side of the screen on which the target and foil objects were presented (left vs. right) was randomly assigned.

2.3. Design

The study was a 2 (Age Group) × 2 (Presentation Timing of Pairings) mixed design. Age group (16- and 20-month-olds) was a between-subjects factor and Presentation Timing of Pairings (massed and interleaved) was a within-subjects factor.

2.4. Procedure

Prior to the beginning of the experiment, infants were seated on a parent's lap. After the infant and parent were positioned appropriately, the lights in the room were dimmed and the calibration procedure began. A five point calibration procedure was used in order to ensure that the reflections of both eyes were centered in the eye-tracking camera's field of view.

2.4.1. Learning phase

Following successful calibration, the learning phase of experiment commenced. The learning phase consisted of

36 learning trials (duration: 4 s each) and 12 attention getter trials (duration: 3 s each), which were grouped into six blocks (see Fig. 1). After every three learning trials, an attention getter was presented. The learning phase ended with the last learning trial of Block 6 (see Fig. 1).

2.4.2. Testing phase

The testing phase began after the attention getter that followed the 36 learning trials. There were 12 testing trials (duration: 8 s each) and 12 attention getter trials (duration: 3 s each). An attention getter was presented before each test trial to re-center the point of gaze. After the final testing trial, the experiment ended. The duration of the entire experiment was 5.2 min.

3. Results

We reasoned that infants' inferences about object-label pairings would be revealed by longer looking to the target object than the distractor object on testing trials. The target object was defined as the object that always co-occurred during learning with the one label heard during each test trial. As noted previously, we predicted that infants at both 16 and 20 months would learn object-label pairings during massed presentation, given that younger infants in previous reports learned from presentations relatively close together in time (e.g., Smith & Yu, 2008). At issue was the possibility that interleaved presentation challenges the acquisition of object-label pairings, perhaps due to limits in aggregation and retrieval of pairings from memory, in which case infants would be expected to look at target and distractor objects equally at test.

3.1. Final test performance

To examine performance on the testing trials, we calculated the mean looking times (i.e., dwell times) to the target and distractor objects (left vs. right side of the screen) across presentation conditions (massed vs. interleaved) and age groups (16- vs. 20-months). We then computed the proportion of looking time to the target object (i.e., target looking time/total looking time). The proportion of looking to the target object, by age group and presentation condition, can be seen in Fig. 2. We then conducted a multivariate ANOVA, with age group as the between subjects factor and the proportion of time looking to the target object for the massed and spaced pairings as the within-subject outcome measures. This analysis revealed a significant interaction of age group and presentation condition, Wilks' Lamda = .880, $F(1,30) = 4.083$, $p = .042$, $\eta_p^2 = .120$, and a marginally significant main effect of age group, $F(1,30) = 3.953$, $p = .056$, $\eta_p^2 = .116$.

To follow up the significant interaction found across the age groups and presentation conditions, post hoc analyses were conducted using six paired-samples comparisons between the proportion looking time to the target for each presentation condition and age group. Bonferroni corrections were used to correct for multiple comparisons. We found that 16-month-olds' performance on the interleaved testing trials was significantly lower than their

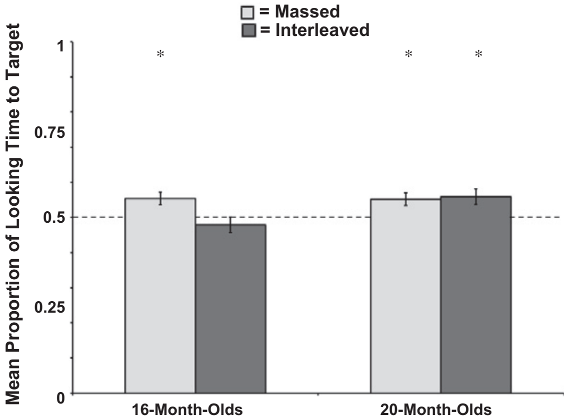

Fig. 2. The mean proportion of looking time to the target object during test trials, by age group and presentation condition (massed vs. interleaved). The dashed line represents chance performance. The $*$ indicates performance significantly different than chance.

performance on the massed testing trials, and significantly lower than the 20-month-olds' performance on both the massed and interleaved testing trials, *ps* < .05. We also conducted an additional four *t*-tests, with Bonferroni corrections, to determine if performance in any of the conditions was significantly above chance performance. These analyses revealed that 16-month-olds' performance on the interleaved testing trials was the only condition not significantly different than chance (all other *ps* < .05). Thus, these analyses suggest that 16-month-old infants were able to successfully learn the massed object-label pairings. Only the 20-month-olds, therefore, provided evidence of learning object-label associations under the (presumably) more challenging conditions presented by interleaved presentation.

Why were there differences in performance across the age groups? In the sections below, we explored several possible explanations for the differences in test performance across development. In particular, we first examined the vocabulary level of the infants in order to determine if language development was related to differences in test performance. We then examined the patterns of attention during the learning phase in order to determine if there were attentional differences that could have potentially contributed to differences in test performance.

3.2. Vocabulary level

One possibility for the performance differences across age groups is that experience learning words supported infant's developing ability to retrieve object-label pairings. In this case, we would expect to see a relation between test performance and vocabulary level, as measured by the MCDI. Alternatively, if domain general processes, such as attention or memory, supported older infants' ability to retrieve pairings, we should expect to see a correlation between age and test performance. Thus, we examined the relationship between age (in months) and language development (MCDI count) in test performance (proportion looking to the target) on interleaved pairings using

Pearson's r. Unsurprisingly, MCDI score was significantly correlated with age, $r(32) = .393$, $p = .026$. However, test performance was significantly related to age, $r(32) = .404$, $p = .022$, but not MCDI score, $p = .290$. This suggests that development in a domain outside of language supported older infants' ability to learn pairings distributed in time.

3.3. Patterns of attention during learning

Another possible domain of development that could have contributed to differences in performance across the age groups is infants' developing attention. For example, it could be that the 20-month-old infants were able to attend more (i.e., for a longer duration) during learning than the 16-month-old infants. To examine this possibility, we calculated the sum looking time across all learning trials during the learning phase for the 16-month-old ($M = 112.7$ s, $SD = 18.4$ s) and 20-month-old ($M = 106.5$ s, $SD = 34.2$ s) infants. We then computed a one-way ANOVA with sum duration of looking during the learning trials as the dependent measure. This analysis revealed no significant difference between the duration of attention during the learning phase between the 16- and 20-month-old infants, $F(1,30) = 2.31$, $p > .05$. Thus, there did not appear to be differences in the overall amount of attention during learning between the 16- and 20-month-old infants.

Although there were no differences in global measures of attention during the learning phase, the ability to selectively attend to information during learning could have contributed to differences in performance. Indeed, selective attention develops dramatically over the first few years of development (e.g., Johnson, 1994; Wu & Kirkham, 2010). Moreover, prior research has proposed that selective attention could be a key mechanism underlying infants' ability to learn cross-situational statistics (e.g., Yu & Smith, 2011).

One possibility is that there were differences between the age groups in the amount of attention to massed vs. interleaved objects during learning trials. That is, the 20-month-old infants may have looked longer at the interleaved objects during learning, perhaps supporting their ability to learn the interleaved pairings. To explore this possibility, we conducted a one-way ANOVA with sum duration of looking time to the interleaved objects during the learning trials as the dependent measure. This analysis revealed no significant difference between the duration of attention to the interleaved objects during the learning phase between the 16- and 20-month-old infants, $F(1,30) = 1.37$, $p > .05$. Thus, there did not appear to be differences in the overall amount of attention to the interleaved objects, during the learning phase, between the 16- and 20-month-old infants.

We also examined specific patterns of selective attention that could be particularly strategic for learning the object-label pairings. In the current experiment, one pattern of attention that could be beneficial for learning the interleaved pairings is to, over the course of one learning block, focus attention away from the repeated, learned objects (i.e., massed objects) and shift attention to the more novel objects (i.e., interleaved objects). That is, shifting visual attention to the objects that are more difficult to learn could potentially support the learning of these object-label pairings.

In order to determine if infants' were engaging in this form of selective attention, we examined infants' looking duration at massed and interleaved objects at the beginning of each block (operationally defined as the first two learning trials of a block) and the end of each block (operationally defined as the last two learning trials of a block). Specifically, we summed the total looking duration across the six blocks for the massed and interleaved objects at the beginning and end of each block. Subsequently, for each age group, we conducted two planned paired-samples comparisons, using Bonferroni corrections, between the looking duration to the massed and interleaved objects at the beginning and end of each block. For the 20-month-old infants, these analyses revealed that there were no significant differences in the looking duration to the massed and interleaved objects at the beginning or end of the blocks, $ps > .05$.

However, for the 16-month-old infants, there was a significant difference in the looking duration to the massed and interleaved objects at the beginning of the blocks, $t(15) = 4.234$, $p = .001$, and at the end of the learning blocks, $t(15) = 2.114$, $p = .006$. At the beginning of the blocks, the 16-month-olds were looking longer at the massed objects ($M = 26.02$ s, $SD = 5.95$ s) than the interleaved objects ($M = 20.58$ s, $SD = 3.01$ s). Moreover, at the end of the learning blocks, 16-month-old infants were looking significantly longer at the interleaved objects ($M = 26.14$ s, $SD = 3.82$ s) than the massed objects ($M = 20.88$ s, $SD = 4.12$ s). This suggests that 16-month-old infants were focusing their attention to the massed objects during the beginning of the learning blocks and shifting their attention the interleaved objects at the end of the learning blocks.

If the 16-month-old infants were looking longer to the last two interleaved objects of a block, it is possible that they could have learned these interleaved pairings to a greater degree than the interleaved pairings presented at the beginning of the blocks. In order to examine this possibility, we calculated the mean proportion of looking to the target at test for the two interleaved objects presented at the beginning of the block (i.e., the first and second learning trials of a block) and at the end of the block (i.e., the fifth and sixth learning trials of a block) for the 16-month-old infants. We then computed one planned paired-samples t-test between looking duration to target on the test trials of interleaved objects presented at the beginning vs. end of the block. The result of this analysis revealed no significant difference in performance between interleaved objects at the beginning and end of a block, $p > .05$. Thus, although the 16-month-old infants shifted their attention to the interleaved objects at the end of the block, this did not result in higher test performance for these object-label pairings.

In sum, there were differences in the patterns of attention during learning between the 16- and 20-month-old infants. The 16-month-old infants demonstrated a seemingly beneficial pattern of selective attention over the course of the learning blocks; these infants initially focused their attention on the repeated stimuli (i.e., the massed objects) and shifted to the more novel objects (i.e., the interleaved objects). However, this shift did not result in higher performance on the interleaved object-label pairings presented at the end of the blocks. Conversely, the 20-month-old infants did not appear to engage in this seemingly beneficial form of selective attention, but were able to learn both the massed and interleaved object-label pairings.

Why did we observe this counter intuitive pattern of results? We suggest that the seemingly beneficial form of selective attention observed in the 16-month-old infants is driven by lower-level familiarity and novelty-seeking behaviors. Although these lower-level behaviors guided attention in a potentially beneficially manner, visual attention alone was not sufficient to learn the object-label pairings (see also Smith & Yu, in press, for a similar hypothesis). Although the 16-month-old infants were attending and encoding potential object-label correspondences, there were likely other cognitive constraints that prevented them from learning information distributed in time.

In addition, the age differences in performance that we observed were likely a result of another domain-general development, memory processes. We grounded our predictions in a long history of research on massed vs. spaced/interleaved learning (dating back to Ebbinghaus, 1885/1964). This research has sought to identify the conditions in which infants and adults typically do and do not learn spaced/interleaved learning events. Thus, the current study provides a framework for understanding the memory processes that could be contributing to developmental differences in performance across the age groups.

4. Discussion

The current study revealed developments during the second year after birth in the ability to learn cross-situational statistics presented over varying timescales. The 16-month-old infants we observed were able to learn the massed, but not interleaved, object-label pairings whereas the 20-month-old infants were able to learn both the massed and interleaved object-label pairings. Test performance was related to age, but not level of vocabulary development, suggesting that domain general developments supported older infants' ability to learn pairings distributed in time. Taken together, these findings bear important theoretical implications for models of cross-situational statistical learning and language development, which are discussed below.

4.1. Selective attention and memory processes in cross-situational statistical learning

During the learning phase, we observed a developmental difference in infants' visual attention during the learning of cross-situational statistics. The 20-month-old infants did not appear to engage in specific patterns of selective attention during learning. However, the 16-month-old infants looked longer at the massed objects at the beginning of the blocks and shifted toward looking at the interleaved objects longer at the end of the blocks. Indeed, by one account, these results are quite counterintuitive; the selective attention demonstrated by younger infants guided visual attention to both massed and interleaved pairings, and thus should have supported learning. However, we obtained no evidence that the 16-month-old infants learned the interleaved object-label pairings. Moreover, 12- and 14-month-olds in a previous study (Smith & Yu, in press) and 16-month-old infants in the current study demonstrated similar patterns in visual attention during learning, but showed differences in final test performance. On the group level, the 12- and 14-months olds (in Smith & Yu, in press) did not learn the object-label pairings regardless of how they were presented whereas the 16-month-olds in the current study were able to learn the massed object-label pairings.

Although the results of the learning trial analyses reveal a developmental trend in patterns of attention during the learning of cross-situational statistics, it is unclear how these results map onto a ready explanation for the developmental differences in final test performance. Consequently, these findings suggest that visual attention alone was not sufficient to support infants' learning and cannot be the sole explanation for the developmental differences in test performance. We argue that another domain general process, memory development, is supporting infants' ability to aggregate and retrieve pairings over time.

In studies of human memory, researchers have sought to characterize changes and developments in retrieval abilities, including developments during the first few years after birth (for a review, see Courage & Cowan, 2009). For example, one persistent finding is that spacing learning events over time promotes learning to a greater degree than massing learning events together in immediate succession (often termed the *spacing effect*; for a meta-analysis, see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006). One predominate theory used to explain spacing and interleaving effects, often termed study-phase retrieval theory (e.g., Thios & D'Agostino, 1976), proposes that spacing and interleaving effects emerge because the interval between presentations allows time for forgetting. Consequently, retrieving prior presentations becomes more difficult. However, this difficulty causes learners to engage in deeper retrieval, strengthening the future retrievability of both the prior and current presentations and slowing the rate of future forgetting.

However, despite the large prevalence of spacing and interleaving effects in learning, it is important to note that there are constraints on the conditions in which these presentation schedules promote learning. For example, a consistent finding is that, if infants do not recall past events during learning, the current learning event is not related to the previous learning event (e.g., time-window hypothesis, Rovee-Collier, Evancio, & Earley, 1995). That is, the two learning events are not aggregated and/or bound together in memory. Thus, rather than conferring a benefit of distributing learning in time, spaced and interleaved presentation schedules deter learning.

This work provides a ready explanation for 16-month-olds' performance; these infants were likely encoding the information for the interleaved object-label pairings, but not aggregating this information with prior pairings. Thus, at the test, the younger infants did not have a sufficient body of information with which to make inferences about the interleaved object-label mappings. In contrast, the 20-month-old infants may have been able to retrieve prior learning during subsequent learning events, supporting the aggregation of object-label correspondences and the ability to later infer object-label mappings.

Although study-phase retrieval theories are the most predominate explanations for spacing and interleaving effects, alternative explanations have been proposed, such as encoding variability theories (e.g., Glenberg, 1979), consolidation theories (e.g., Landauer, 1969), and deficient processing theories (e.g., Hintzman, 1974; for a review these theories, see Delaney, Verkoeijen, & Spirgel, 2010). The current research has implications for these general theories of learning in that it is a demonstration of how developmental changes in the learner can influence the interaction of basic cognitive processes. For example, one class of deficient processing theories, often termed inattention theory (e.g., Hintzman, 1974), proposes that spacing effects arise because massing learning events reduces the amount of attention learners pay to repeated presentations. Consequently, there is less memory processing and storage for these items, compared to more novel spaced/interleaved items. Consistent with inattention theory, we observed a decrease in attention in 16-month-olds toward massed objects over the course of the learning blocks. However, inconsistent with this theory, we did not observe that this led to more learning of the interleaved object-label pairings. Instead, the 16-month-old infants were only able to learn the massed object-label pairings. Thus, the current results inform inattention theory by suggesting that learners may decrease attention to repeated massed items, but this does not necessarily result in different learning outcomes. Critically, the developmental state of the learner may moderate (a) the degree to which learners engage in patterns of inattention during learning and (b) the role of memory in learning outcomes, such as in the case of cross-situational statistical learning.

4.2. Memory development and theories of cross-situational statistical learning

What happens when infants are unable to retrieve the past? Certainly the current experiment as well as a long history of research on infant memory (e.g., Courage & Cowan, 2009) suggest that there are significant constraints on infants' ability to aggregate and recall prior learning events. Memory development, and the developing ability to retrieve information, has been used to explain rapid periods of language development (e.g., Dapretto & Bjork, 2000; Gershkoff-Stowe, 2002). This work has suggested that developmental changes in domain general retrieval abilities result in an apparent vocabulary burst in language production. The current work is consistent with this theoretical account – there were striking differences in the ability to retrieve and learn object-label pairings across time in the pre-vocabulary burst (16 months) and post-vocabulary burst (20 months) age groups. Thus, theories of cross-situational statistical learning need to account for infants' developing ability to retrieve information over time.

To date, there are two primary theories of cross-situational statistical learning, associative learning accounts (e.g., Smith & Yu, 2008; Yu & Smith, 2011) and hypothesis testing accounts (e.g., Frank et al., 2009; Vouloumanos & Werker, 2009; Xu & Tenenbaum, 2007). In both of these theories, retrieving the past is a critical process underlying learning (for a review, see Yu & Smith, 2012). For example, in associative learning accounts, learners track co-occurrence probabilities that eventually develop into a matrix of word–referent associations. Word mapping is subsequently guided by the retrieval of association strengths. Similarly, in hypothesis testing accounts, learners must retrieve specific hypotheses about word–referent pairings and, in the face of current evidence, select among the retrieved hypotheses to infer correct mappings. In sum, according to theories of cross-situational learning, successful word mapping is dependent upon retrieval of past learning. In order to account for how infants develop the ability to retrieve past learning, future research should examine how factors of the learning environment, such as the number of exposures and varying timing schedules, can support infants' developing ability to retrieve object-label pairings.

We suggest that infants go through an extended period of encoding information before it is aggregated, such as in an associative matrix (in associative learning theories; e.g., Yu & Smith, 2011) or data set by which hypotheses can be formed and tested (in hypothesis-testing theories; e.g., Xu & Tenenbaum, 2007). It may be that simply encoding co-occurrence information is the foundation for cross-situational statistical learning and word mapping. Over time and with experience, infants' ability to retrieve the past develops, which supports later aggregation and retrieval of prior learning. Indeed, before we make sense of a seemingly infinite amount of information, we may need to first take it all in – by encoding perceptual, temporal, and contextual information.

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References

Bulf, H., Johnson, S. P., & Valenza, E. (2011). Visual statistical learning in the newborn infant. *Cognition, 121*, 127–132. http://dx.doi.org/10.1016/j.cognition.2011.06.010.

Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin, 132*, 354–380. http://dx.doi.org/10.1037/0033-2909.132.3.354.

Courage, M., & Cowan, N. (2009). *The development of memory in infancy and childhood*. New York, NY: Psychology Press.

Dapretto, M., & Bjork, E. L. (2000). The development of word retrieval abilities in the second year and its relation to early vocabulary growth. *Child Development, 71*, 635–648. http://dx.doi.org/10.1111/1467-8624.00172.

Delaney, P. F., Verkoeijen, P. P. J. L., & Spirgel, A. (2010). Spacing and testing effects: A deeply critical, lengthy, and at times discursive review of the literature. In B. H. Ross (Ed.). *Psychology of learning and motivation: Advances in research and theory* (Vol. 53, pp. 63–147). New York, NY: Elsevier.

Ebbinghaus, H. (1964). In H. A. Ruger, C. E. Bussenius, & E. R. Hilgard (Trans. Eds.), Memory: A contribution to experimental psychology. New York: Dover Publications. [Original work published in 1885].

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., & Pethick, S. J. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development, 59*(5, serial 242). http://dx.doi.org/10.2307/1166093.

Frank, M. C., Goodman, N. D., & Tenenbaum, J. B. (2009). Using speakers' referential intentions to model early cross-situational word learning. *Psychological Science, 20*, 578–585. http://dx.doi.org/10.1111/j.1467-9280.2009.02335.x.

Gershkoff-Stowe, L. (2002). Object naming, vocabulary growth, and the development of word retrieval abilities. *Journal of Memory and Language, 46*, 665–687. http://dx.doi.org/10.1006/jmla.2001.2830.

Glenberg, A. M. (1979). Component-levels theory of the effects of spacing of repetitions on recall and recognition. *Memory and Cognition, 7*, 95–112.

Hintzman, D. L. (1974). Theoretical implications of the spacing effect. In R. L. Solso (Ed.), *Theories in cognitive psychology: The Loyola symposium* (pp. 77–97). Potomac, MD: Erlbaum.

Johnson, M. H. (1994). Visual attention and the control of eye movements in early infancy. *Attention and Performance, 15*, 291–310.

Kachergis, G., Yu, C., & Shiffrin, R. M. (2012). An associative model of adaptive inference for learning word–referent mappings. *Psychonomic Bulletin and Review, 19*, 317–324. http://dx.doi.org/10.3758/s13423-011-0194-6.

Landauer, T. K. (1969). Reinforcement as consolidation. *Psychological Review, 76*, 82–96.

Merriman, W. E., & Bowman, L. L. (1989). The mutual exclusivity bias in children word learning. *Monographs of the Society for Research in Child Development, 54*, 1–123.

Onnis, L., Edelman, S., & Waterfall, H. (2011). Local statistical learning under cross-situational uncertainty. In L. Carlson, C. Hölscher, T. Shipley (Eds.), Proceedings of the 33rd annual meeting of the cognitive science society conference.

Quine, W. V. O. (1960). *Word and object*. Cambridge, MA: MIT Press.

Rovee-Collier, C., Evancio, S., & Earley, L. A. (1995). The time window hypothesis: Spacing effects. *Infant Behavior and Development, 18*, 69–78. http://dx.doi.org/10.1016/0163-6383(95)90008-X.

Siskind, J. M. (1996). A computational study of cross-situational techniques for learning word-to-meaning mappings. *Cognition, 61*, 39–91. http://dx.doi.org/10.1016/S0010-0277(96)00728-7.

Smith, L. B. (2000). How to learn words: An associative crane. In R. Golinkoff & K. Hirsh-Pasek (Eds.), *Breaking the word learning barrier* (pp. 51–80). Oxford: Oxford University Press.

Smith, K., Smith, A. D. M., & Blythe, R. A. (2010). 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., & 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.

Suanda, S. M., & Namy, L. L. (2012). Detailed behavioral analysis as a window into cross-situational word learning. *Cognitive Science, 36*, 545–559. http://dx.doi.org/10.1111/j.1551-6709.2011.01218.x.

Thios, S. J., & D'Agostino, P. R. (1976). Effects of repetition as a function of study-phase retrieval. *Journal of Verbal Learning and Verbal Behavior, 15*, 529–536. http://dx.doi.org/10.1016/0022-5371(76)90047-5.

Tomasello, M. (1992). The social bases of language acquisition. *Social Development, 1*, 67–87. http://dx.doi.org/10.1111/j.1467-9507.1992.tb00135.x.

Vlach, H. A., Ankowski, A. A., & Sandhofer, C. M. (2012). At the same time or apart in time? The role of presentation timing and retrieval dynamics in generalization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 246–254. http://dx.doi.org/10.1037/a0025260.

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.

Wu, R., & Kirkham, N. Z. (2010). No two cues are alike: Depth of learning during infancy is dependent on what orients attention. *Journal of Experimental Child Psychology, 107*, 118–136. http://dx.doi.org/10.1016/j.jecp. 2010.04.014.

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. (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., Boyer, T. W., Smith, L. B., & Yu, C. (2013). Probabilistic cue combination: Less is more. *Developmental Science, 16*, 149–158. http://dx.doi.org/11/desc.12011.