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CHILD DEVELOPMENT

Experience and maturation: The contribution of co-occurrence regularities in language to the development of semantic organization

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Abstract

With development knowledge becomes organized according to semantic links, including early-developing associative (e.g., juicy–apple) and gradually developing taxonomic links (e.g., apple–pear). Word co-occurrence regularities may foster these links: Associative links may form from direct co-occurrence (e.g., juicy–apple), and taxonomic links from shared co-occurrence (e.g., apple and pear co-occur with juicy). Four experiments (2017–2020) investigated this possibility with 4- to 8-year-olds (N = 148, 82 female) and adults (N = 116, 35 female) in a U.S. city with 58.6% White; 29.0% Black, and 5.8% Asian demographics. Results revealed earlier development of the abilities to form direct (ds>0.536) than the abilities to form shared co-occurrence-based links (ds>1.291). We argue that the asynchronous development of abilities to form co-occurrence-based links may explain developmental changes in semantic organization.

Our knowledge about the world is not simply a repository of stored information. Instead, it functions as a *semantically organized* network, in which concepts, denoted by words, are linked by semantic relations (Cree & Armstrong, 2012; Jones et al., 2015; McClelland & Rogers, 2003). It is difficult to overestimate the importance of semantic organization of human knowledge, as it supports a myriad of cognitive functions. For example, semantic links between *hiking*, *tent*, *backpack*, and *boots* can help us discuss, retrieve knowledge about, and plan what to bring on a hiking trip, even if we have never hiked before. In language alone, semantic links play many roles. For example, semantic links between *apple*, *eat* and *juicy* can support anticipating that the utterance "I went to the orchard to pick some ripe, juicy …" is likely to be completed with "apple" or inferring that "I'd like a ripe, juicy apple" refers to a desire to *eat* an apple, even though eating was never mentioned.

It is hardly controversial that semantic knowledge becomes organized with development, and that experiences acquired during development are important for driving this process (Coley, 2012; Gobbo & Chi, 1986; Unger & Fisher, 2019; Vales et al., 2020). What remains less clear is *what* aspects of experience *drive* the development of semantic organization, and *how*.

Here, we first provide an overview of the development of semantic organization. We then outline a potentially powerful candidate driver of this development: Statistical regularities of word use in language that can in principle foster semantic links between concepts denoted by words. Although the presence of these regularities has been noted for decades (e.g., Harris, 1954; Landauer & Dumais, 1997; Lewis et al., 2019; Lund & Burgess, 1996; Miller & Charles, 1991), surprisingly little is known about how they may contribute to the development of semantic organization. Critically, we do not know whether (1) the mere accumulation of exposure to these regularities is enough to foster the development of semantic links or (2) this exposure fosters semantic links

Olivera Savic and Layla Unger are co-first authors on the article, and the present order is purely alphabetical.

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only in conjunction with the *maturation* of abilities to form semantic links from exposure. We therefore present four experiments investigating whether abilities to form semantic links from such regularities undergo development, and how this development may help explain developmental changes in semantic organization.

Two critical types of semantic links: Associative and taxonomic

Semantic knowledge refers to our general knowledge about the world. For example, it includes everything we know about apples, juiciness, hiking, and ghosts, including their properties, the words denoting these concepts, and the semantic links that connect these to other concepts in our memory (Jones et al., 2015; McClelland & Rogers, 2003). Two critical types of semantic links that organize human semantic knowledge are associative and taxonomic links.

There is extensive evidence that semantic organization is shaped by *associative* semantic links (also referred to as *thematic*) from early development onward. Associative links, such as those linking *apple*, *eat* and *juicy*, connect concepts whose labels or real-world counterparts are often experienced together (Blaye et al., 2006; Fenson et al., 1989; Lin & Murphy, 2001; Unger, Savic, et al., 2020). Associative links play a key role in semantic organization and the intelligent processes that depend on it throughout development. For example, associative links support language comprehension as they constrain the set of candidate words that are likely to be combined to form meaningful sentences (e.g., the word *apple* is understood faster when preceded by *juicy* than *fluffy*; Arnon & Snider, 2010; Kutas & Federmeier, 2000; McDonald & Shillcock, 2003). Moreover, associative links can also support word learning. For example, the associative link between *apple* and *juicy* can support inferring that *mipp* is a fruit upon hearing "*juicy mipp*" (Sloutsky et al., 2017). These and other contributions of associative links to semantic organization emerge early in development (e.g., Blaye et al., 2006; Fenson et al., 1989; Sloutsky et al., 2017; Unger, Savic, et al., 2020), and persist into adulthood (e.g., Kutas & Federmeier, 2000; Lin & Murphy, 2001).

Associative links are often contrasted with *taxonomic* links, which connect concepts that are similar in meaning and denote members of the same stable semantic category, such as fruits, mammals, or furniture. For example, *apple* and *pear* are taxonomically related because they belong to the category of fruits, and thus share many stable properties, such as having seeds or containing sugars. Like associative links, taxonomic links are fundamental to semantic organization. In particular, they support a central facet of human intelligent behavior: The ability to generalize knowledge from known to novel. For example, upon learning that apples are rich in vitamins, people can generalize this knowledge to pears and other fruits (López et al., 1992; Osherson et al., 1990; Sloutsky, 2010). Similarly, because taxonomic links connect words similar in meaning, they can allow us to learn that the word *dax* may refer to a fruit from "That jam was made from apples, pears, and daxes" (Sloutsky et al., 2017). In contrast to the associative links that may emerge early in childhood, typically before the age of four (Fenson et al., 1989; Inhelder & Piaget, 1964; Lucariello et al., 1992), taxonomic links emerge more gradually over semantic development, and are typically not robust before the age of six (Blaye et al., 2006; Fisher, 2011; Gentner & Namy, 1999; Lucariello et al., 1992; Unger, Savic, et al., 2020).

Where do associative and taxonomic links come from?

Characterizing the links that organize semantic knowledge and when they emerge in development is informative, but insufficient for a complete understanding of *how* semantic organization develops. Instead, it is critical to understand what *drives* the formation of these semantic links. Traditionally, due to their different developmental trajectories, the origins of associative and taxonomic links have been treated as entirely separate.

Associative links are typically assumed to come from observing labels or real-world referents of concepts *reliably* occurring together in the environment (McNeill, 1963). Because of this presumed origin, they have often been dismissed as non-semantic in nature (Inhelder & Piaget, 1964; Lucas, 2000). Thus, theoretical accounts of semantic development have either overlooked associative links (e.g., McClelland & Rogers, 2003), or treated them as an immature facet of semantic organization that becomes overwritten with development (Inhelder & Piaget, 1964; Lucariello & Nelson, 1985).

In contrast with associative links, many accounts of the development of semantic organization focus on taxonomic links. A widely adopted and substantially supported perspective is that these links can form by detecting the regularity with which members of taxonomic categories share similar features or perform similar functions (McClelland & Rogers, 2003; Quinn & Eimas, 1997; Rosch et al., 1976; Sloutsky, 2010). For example, *robin* and *canary* may become linked as they are both observed to have wings, feathers, and fly. According to this perspective, taxonomic links develop with the accumulation of information about the shared features and functions of concepts (e.g., McClelland & Rogers, 2003), and a maturing ability to optimize learning when concepts share only a few, taxonomic category-relevant features or functions (Sloutsky, 2010).

Together, previous theoretical and empirical work has made substantial inroads into understanding the drivers of the development of semantic organization. However,

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as we argue below, much of previous research substantially underappreciated the role of associative links in the development of semantic organization, and their potential contribution to taxonomic links. In the following section, we review an alternative theoretical account that offers a coherent, parsimonious explanation of the development of both associative and taxonomic links. We refer to this proposal as the Co-Occurrence Account (Sloutsky et al., 2017). This account is not intended to be exclusive of other accounts of the development of semantic organization: Both the input highlighted by the Co-Occurrence account and observable features may contribute to semantic organization. However, in contrast to prior accounts, the Co-Occurrence Account assumes that early-emerging associative links form a *foundation* for building taxonomic knowledge. According to this account, ubiquitous co-occurrence statistics of word use in language foster associative links that *in turn* may foster the emergence of taxonomic links. Finally (and critically), this account offers testable predictions about the developmental trajectory of semantic organization.

A key role for co-occurrence regularities in the development of semantic organization

Words tend to co-occur in language in predictable ways. For example, *apple* and *pear* reliably co-occur with *juicy*, whereas *happy* and *sad* reliably co-occur with *feel*. Critically, these *reliable* co-occurrences go beyond mere frequency of co-occurrence. Many words frequently co-occur simply because at least one of them is a highly frequent word (e.g., "*an* apple", "*is* happy"). Instead, the reliable word co-occurrences consist of *interdependencies* between words, in which the probability of encountering one word is in part dependent upon encountering another, above and beyond their respective frequencies. Here, we consider how concepts, denoted by words, may become semantically organized from exposure to these simple regularities of words use.

According to the Co-Occurrence account, reliable co-occurrence regularities can foster associative (or syntagmatic) links between concepts whose labels *directly co-occur*, such as *juicy—apple* and *juicy—pear* (Figure 1). Critically, sensitivity to co-occurrence regularities can also support taxonomic (or paradigmatic) links between concepts similar in meaning, such as *apple* and *pear*, even when words for such concepts do not directly co-occur. Instead, words for concepts similar in meaning tend to *share* each other's patterns of direct co-occurrence with other words, such as *juicy* or *eat* (Ervin, 1961; Harris, 1954; Hofmann et al., 2018; Miller & Charles, 1991). Thus, *reliable* word co-occurrence can foster both associative and taxonomic links. The Co-Occurrence account offers two candidate explanations of how these regularities may drive the typical developmental trajectory in which associative links emerge early and are gradually supplemented by taxonomic links, the *Experience* and *Experience-plus-maturation* accounts.

Experience account

One possibility is that developmental changes in semantic organization may be driven by the mere accumulation of *exposure* to co-occurrence regularities. According to this account, developmental changes in semantic organization occur as accumulation of experience initially fosters associative links based on direct co-occurrence, which then foster taxonomic links based on shared co-occurrence (Ervin, 1961; McNeill, 1963, 1966). This account assumes that abilities to form links based on direct co-occurrence mature early, probably in infancy. Moreover, it assumes that robust direct co-occurrence links are sufficient for the formation of shared co-occurrence links (e.g., McNeill, 1963). This assumption is a key characteristic of models that capture human semantic organization based on word co-occurrence in language (Hofmann et al., 2018; Jones & Mewhort, 2007; Landauer & Dumais, 1997; Lund & Burgess, 1996; Mikolov et al., 2013), some models of the formation of co-occurrence-based memories (Schapiro et al., 2017), and proposals that identify these models as potential models of human semantic development (Sloutsky et al., 2017). There are two strong arguments for the plausibility of this proposal. First, extensive evidence attests that co-occurrence regularities that can foster semantic links are abundant in language (Hofmann et al., 2018; Jones & Mewhort, 2007; Landauer & Dumais, 1997; Lund & Burgess, 1996; Mikolov et al., 2013), including input to

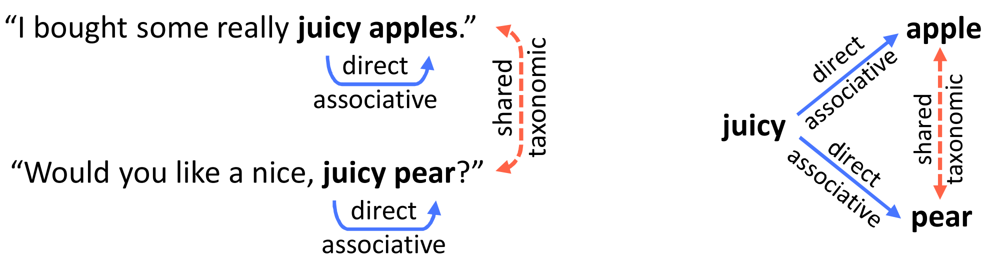

FIGURE 1 Direct and Shared co-occurrence regularities in language that can form associative and taxonomic links

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young children (Asr et al., 2016; Fourtassi, 2020; Huebner & Willits, 2018). Second, even infants show sensitivity to co-occurrence regularities in a variety of domains (e.g., Kirkham et al., 2002; Saffran et al., 1996, 1999), including to direct co-occurrences of words in language (Wojcik & Saffran, 2015).

Experience-plus-maturation account

Although the Experience account is plausible, exposure to co-occurrence regularities *alone* may not be sufficient to explain the development of semantic organization. Instead, *abilities to learn semantic links* from exposure to co-occurrence regularities may also undergo development. According to this perspective, the *same exposure* will contribute *differently* to the formation of semantic links across development. For example, abilities to form links based on direct co-occurrence may improve with development (Arciuli & Simpson, 2011; Raviv & Arnon, 2018; Shufaniya & Arnon, 2018). Like the Experience account, this possibility would explain the development of associative before taxonomic links because links based on direct co-occurrence are a necessary precursor for forming links based on shared co-occurrence. Alternatively, the formation of links based on direct co-occurrence may be necessary but insufficient for the formation of links based on shared co-occurrence: Instead, abilities to form links based on shared co-occurrence may themselves develop (Bauer & San Souci, 2010; Miller-Goldwater et al., 2021; Schlichting et al., 2017, 2021).

Present study

The present study tested the core proposal of the Co-Occurrence account that exposure to co-occurrence regularities in language can foster associative and taxonomic links in semantic development. We investigated the contributions of word co-occurrence regularities across ages that capture substantial changes in semantic organization (adults vs. 4-year-olds in Experiments 1–3, and adults vs. 5- to 6-year-olds and 7- to 8-year-olds in Experiment 4).

The present study was further designed to disentangle two ways in which exposure to co-occurrence regularities may explain the typical developmental trajectory of semantic organization in which associative links emerge early and are gradually supplemented by taxonomic links. First, mere exposure to co-occurrence regularities may be sufficient to foster both direct and shared co-occurrence links throughout development (*Experience account*). Alternatively, exposure to co-occurrence regularities may only foster links in conjunction with maturation of abilities to form links based on co-occurrence (*Experience-plus-maturation account*). To disentangle these possibilities, we presented children and adults with training sentences rich in direct and shared co-occurrence regularities that could foster *new* semantic links between familiar and novel words (Figure 2). Two critical aspects of this design are that (1) children and adults were given the *same amount of exposure* to co-occurrence regularities, and (2) the new semantic links could be formed *solely from the co-occurrence* regularities. Given these experimental constrains, the Experience account predicts similar performance in children and adults, whereas the Experience-plus-maturation account predicts developmental differences due to the maturation of abilities to form links based on co-occurrence.

Guided by these theoretical assumptions, we conducted two sets of analyses that tested (a) developmental differences in abilities to form links based on direct and shared co-occurrence (Experiments 1–4) and (b) the interdependence of development of these abilities (Experiments 2–4). Given that these analyses tested theoretical assumptions, they are both confirmatory in nature.

We assessed participants' formation of new semantic links in two tasks: Sentence completion and Label extension. Following the logic of free association tasks, the Sentence completion task presented participants with stem sentences that contained a cue word from training and assessed whether participants completed these sentences using another word that either directly co-occurred or shared co-occurrence with the cue word. The Label extension task used a variant of a word learning task to assess the formation of new semantic links between familiar (e.g., *apple*) and novel words (e.g., *mipp*). Specifically, we assessed whether participants labeled pictures of familiar words (e.g., apples) and items from the same semantic category (e.g., fruits) using the novel words with which familiar words directly co-occurred or shared co-occurrence. Thus, accurate performance on both tasks could *only* be achieved by forming new semantic links based on the reliable co-occurrences of words during training.

EXPERIMENT 1

To measure the contributions of co-occurrence regularities to the formation of semantic links across development, young learners (4-year-olds) and adults heard sentences in which pseudowords directly co-occurred or shared co-occurrence with familiar words. For example, as illustrated in Figure 2, the pseudoword *foobly* and familiar word *apple* could become linked because they reliably directly co-occurred in the same sentences (i.e., *foobly* reliably preceded *apple*). In addition, the pseudoword *mipp* and familiar word *apple* could become linked because they shared each other's direct co-occurrence with same word, *foobly*, across different sentences. To ensure that links could only form based on co-occurrence

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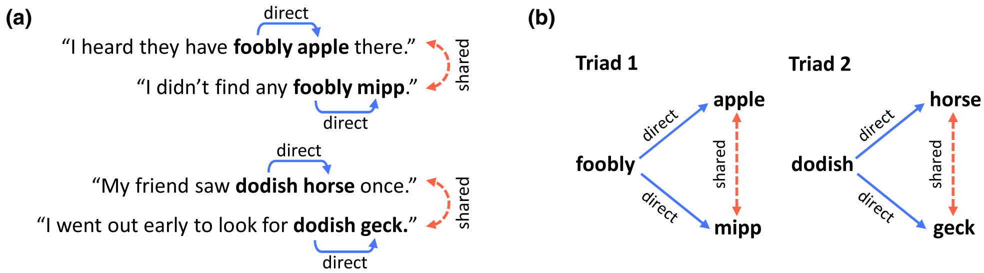

FIGURE 2 Examples of training sentences (panel a) and illustration of the two triads (panel b)

regularities, sentences provided no additional semantic information from which the meanings of the novel words could be derived (e.g., "Sally saw a foobly mipp"). More specifically, although participants could use syntactic cues to learn that pseudoadjectives (e.g., *foobly*) refer to properties, and pseudonouns (e.g., *mipp*) refer to concrete entities, this information did not signal *which* pseudoadjectives and pseudonouns reliably co-occurred. Following training, we measured the formation of co-occurrence-based links using two tasks—Sentence Completion and Label Extension—described below.

The inclusion of pseudowords allowed us to examine the development of abilities to form *novel* semantic links based only on co-occurrence regularities. Moreover, the inclusion of familiar words allowed us to test not only whether novel words became linked with the specific familiar words they shared co-occurrence within training (e.g., *mipp*-*apple*), but also to other members of the category the familiar word belongs to (e.g., *mipp*-*banana*). Evidence that links based on shared co-occurrence can support such generalization is critical because generalization is the key property of taxonomic links that may be formed from shared co-occurrence.

Method

Participants

Participants were thirty-two 4-year-olds (M_{age} = 52.0 months, range 48.1–59.8 months, 16 female) and 28 adults (M_{age} = 19.6 years, range 18.0–26.3 years, 19 female). The sample size was determined based on power analyses using the effect size from a pilot experiment that tested developmental differences in the formation of shared co-occurrence links using the Label Extension task. To detect the effect size of d = 2.285 obtained in the pilot experiment, with 80% power using a paired t-test with alpha at .05, it would be sufficient to have a sample of 5 participants per age group. To account for the differences in design (i.e., additional test, shorter training), we recruited a minimum of 30 participants per age group. Two additional adult participants were excluded due to a failure to follow the instructions.

In this and other experiments reported here, children were recruited from preschools and childcare centers located in middle-class suburbs of Columbus, Ohio. Adult participants were The Ohio State University undergraduate students. Children were recruited on the basis of returned parental permission forms. They were tested during their regular school hours in a quiet room in their preschool or childcare center. Adults provided informed consent and received course credit for participation. They were tested in the laboratory on campus.

Given that children were recruited from preschools and childcare centers, race and ethnicity information was not possible to collect. In all reported experiments, children were recruited from ethnically diverse suburban locations (58.6% White; 29.0% Black or African American; 6.2% Hispanic or Latino; 5.8% Asian; according to U.S. Census Bureau, Population Estimates Program; https://www.census.gov).

This study was approved by the Ohio State University Institutional Review Board (Protocol Title: Comprehensive protocol for cognitive development research, Protocol Number: 2004B0422). Data for all four experiments were collected between October 2017 and December 2020 (Experiments 1–2: October 2017–November 2018; Experiment 3: September 2019–February 2020; Experiment 4: October 2020–December 2020).

Materials

The training stimuli were two triads of words (Triad 1: *foobly—apple—mipp*; Triad 2: *dodish—horse—geck*). Each triad consisted of a pseudoadjective (*foobly* or *dodish*), a familiar noun (*apple* or *horse*), and a pseudonoun (*mipp* or *geck*; see Figure 2). Within each triad, the pseudoadjective was paired with (a) the familiar noun and (b) the novel pseudonoun. To ensure that pseudowords did not evoke any meaning related to selected familiar nouns, pseudowords were selected based on a norming study (for details see Supporting Information).

Each of the four pairs of words (*foobly apple*; *foobly mipp*; *dodish horse*; *dodish geck*) from the triads was embedded in 10 unique sentence frames, for a total of 40 unique training sentences. To ensure that semantic links formed between the words from the triads could

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be attributed only to exposure to co-occurrence regularities, sentences frames did not convey any cues to pseudoword meaning. All the sentences were recorded by a female speaker in a child friendly voice.

For the Sentence Completion task, we constructed 30 stem sentences (see Procedure and Figure 3). Stem sentences, such as "*Jimmy saw a foobly* …", consisted of a sentence frame (e.g., "*Jimmy saw a*") followed by one of the words from the Triads (i.e., "*foobly*"). For each of the six words from the Triads, five unique sentence frames were constructed.

The stimuli in the Label Extension task were the four pseudowords from the Triads, 24 pictures of apples and other fruits and 24 pictures of horses and other four-legged mammals.

Procedure

The experiment had three parts: Training, Sentence Completion, and Label Extension (Figure 3). The procedure was identical for children and adults, with the exception that an experimenter-controlled stimulus presentation and recorded responses for children, whereas adults completed the experiment independently.

Training

Participants were told that they would hear "silly stories" told by a character, "Jimmy," who sometimes uses "silly words." They heard two stories, each containing the full set of 40 training sentences, while watching child-friendly videos without narrative content.

Sentence completion

To assess the formation of new links between words based on co-occurrence, we adapted a child-friendly version of McNeill's (1963) free association paradigm. In free association tasks, participants are given one word as a cue, and respond with the first word that comes to their minds. However, this is an unconstrained task that children often struggle to understand (Wojcik & Kandhadai, 2019). To be more comprehensible to children, the Sentence Completion task presented participants with stem sentences that ended with a cue word (i.e., one of the six words from the Triads), and participants were asked to complete the sentences with one of "Jimmy's words" (Figure 3). If the stem sentence ended with a pseudoadjective (e.g., *foobly*), participants could rely on direct co-occurrence, and complete the sentence with either the pseudonoun or the noun from the same Triad. If the stem sentence ended with a pseudonoun or a noun, participants could rely on either direct or shared co-occurrence to complete the sentence. For example, the stem sentence "*Jimmy saw a mipp* ____", could be completed with either *foobly* (direct co-occurrence) or *apple* (shared co-occurrence). Full instructions and stem sentences are presented in Supporting Information.

Although production tasks of this sort have been widely used to test existence of links between words (Ervin, 1961; Nelson, 1977; Wojcik & Kandhadai, 2019) they come with two weaknesses: (1) they measure only participants' dominant responses, and (2) they can be biased toward some types of responses. Thus, we suspected that participants in the Sentence completion task may primarily respond based on direct co-occurrence, because (a) these regularities are easier to learn and may therefore dominate responses, and (b) these responses are more felicitous given that they respect the word order of training sentences. Therefore, we designed the Label Extension task to independently assess participants' ability to form links based on shared co-occurrence.

Label extension

In this task, participants saw images of apples and horses (i.e., the familiar words from the Triads) and other fruits and mammals. Participants' task was to label these images using one of the two pseudonouns (i.e., *mipp* or *geck*), that each shared co-occurrence with one of the familiar nouns in Training sentences (see Figure 3). To perform well on apple and horse trials, participants needed to use the link between familiar and pseudonouns that could be formed based on shared co-occurrence (apple—*mipp*, horse—*geck*). On fruit and mammal trials, participants need to generalize this link to label images of items that are from the same taxonomic category as familiar nouns (fruit (apple)—*mipp*; mammal (horse)—*geck*). Thus, consistently labeling apples and other fruits with the pseudoword *mipp* and horses and other mammals with the pseudoword *geck* would indicate that a participant formed and generalized links based on shared co-occurrence. There were 48 trials, including 12 apple and horse trials and 36 fruit and mammal trials.

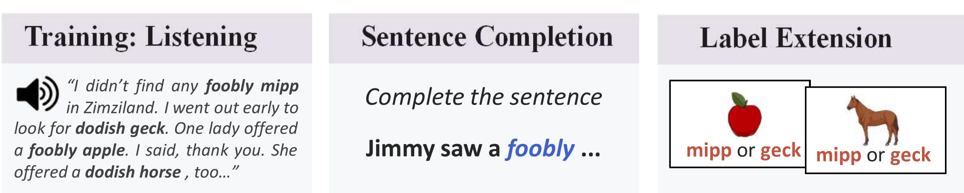

FIGURE 3 Illustration of the experimental design used in Experiments 1–4

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Results

All analyses were conducted in the R environment for statistical computing (R Core Team, 2022). Analyses using mixed effects logistic regression were conducted using the lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and afex (Singmann et al., 2022) packages. Data and analysis scripts are available at https://osf.io/6bvcq.

Sentence completion

Preliminary analyses

We first identified responses as "valid" (i.e., responses that used words from Triads) or "invalid" (i.e., responses with other words). Four-year-olds produced valid responses on 93.1% of all trials, whereas adults gave valid responses on 77.0% of all trials. Adult invalid responses primarily consisted of words from training that were not from the Triads. Further analyses included valid responses only. We additionally excluded word repetitions (e.g., responding "foobly" to "foobly") and multiple word responses (e.g., responding "dodish mipp" to "geck"). This resulted in a removal of 2.0% of adult and 4.8% of child responses.

Main analyses: Formation of direct and shared links

We first coded valid responses based on Congruence (Congruent = same triad as the cue; Incongruent = different triad than the cue), and Type (Direct; Shared). For each participant, we then calculated the proportions of Congruent responses based on direct and shared co-occurrence, corrected for guesses. Specifically, for each cue (e.g., *apple*, Triad 1 noun) and response Type (e.g., Direct), we subtracted the proportion of Incongruent (e.g., *dodish*, Triad 2 pseudoadjective) from the proportion of Congruent responses (e.g., *foobly*, Triad 1 pseudoadjective). For example, when the cue word was *apple*, if 50% of a participant's Direct responses were Congruent (i.e., *foobly*), and 50% were Incongruent (i.e., *dodish*), the raw proportions of Congruent and Incongruent Direct responses would each be .50, and the proportion corrected for guessing would be 0. Corrected values thus ranged from 0 (random guessing), to 1 (all responses Congruent). For details, see Supporting Information.

Both age groups made Direct responses at rates above the chance level of 0, one sample t-tests against chance, ts>5.74, ps<.001, ds>1.01 (Figure 4). However, there were significant developmental differences, $t(58) = 4.44$, $p < .001$, $d = 1.15$. Adults produced higher proportions of Direct responses than children (children: $M = .19$, $SD = .19$; adults: $M = .47$, $SD = .29$).

The proportion of Shared responses was very low for both age groups (children: $M = .08$, $SD = .12$; adults: $M = .19$, $SD = .24$), but significantly greater than chance level of 0, both ts>4.01, ps<.001, ds>0.71. There were also significant developmental improvements, $t(58) = 2.30$, $p = .025$, $d = 0.594$ (Figure S1). Note that the low rate of Shared co-occurrence responses may be due to the fact that Sentence Completion only measures *dominant* responses. Thus, any dominance of responding based on direct co-occurrence (e.g., responding *foobly* to *apple*) collaterally precludes responding based on shared co-occurrence (e.g., responding *mipp* to *apple*), even if shared co-occurrence links are formed. Therefore, the Label Extension task was used as the primary assessment of the links based on shared co-occurrence.

Label extension

The accuracy of five participants (all adults) was below 0.25, and thus well below chance. Because this performance was uninterpretable, their data were excluded from the further analyses. Importantly, the exclusion of these participants did not change the results (see Section S-5 and Figure S4 for the analyses and figures which include the whole sample of participants).

We found striking developmental differences in accuracy on the Label extension task (see Figure 4). We analyzed participants' accuracy by fitting a mixed effects logistic regression with a fixed effect of Age (levels: 4-year-old and Adult) and random intercepts for participants and stimuli. We settled on a model that included only random intercepts given that this was the maximal random effects structure that converged and did not result in a singular fit. p-Values were computed using parametric bootstrap test. We followed this approach in all mixed effects logistic regression analyses reported across the four experiments. The model revealed a significant effect of Age, $\chi^2(1) = 60.23$, $p < .001$, with adults outperforming children. We followed up this analysis by testing whether each Age group performed above chance. Whereas children performed no different from the chance level of .50, $t(31) = 0.90$, $p = .754$, $d = 0.158$, adults were above chance, $t(22) = 13.56$, $p < .001$, $d = 2.827$. Furthermore, only 5 out of 32 children (16%) had above chance accuracy (i.e., above 0.62 based on binomial distribution). In contrast, all but one adult participant (96%) performed above chance.

Discussion

The results of Experiment 1 support the Co-Occurrence account's proposal that children and adults form semantic links based on exposure to co-occurrence regularities in language. Moreover, we found evidence that the formation of both links based on direct and shared co-occurrence improved with age, with particularly striking developmental differences in the formation of links based on shared co-occurrence.

The results of Experiment 1 can shed light on the role of experience and maturation in the development of semantic organization. These results suggest that the more

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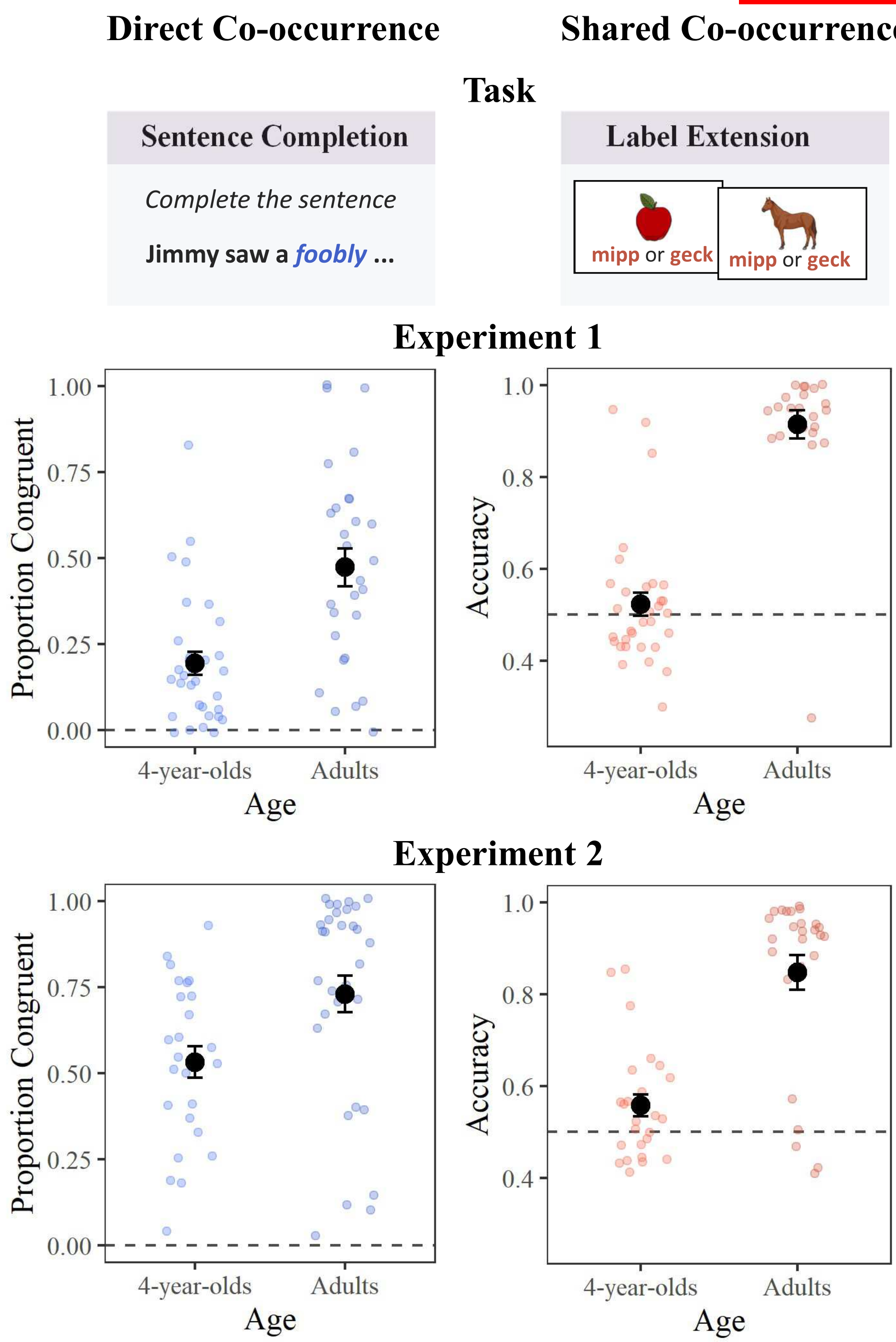

FIGURE 4 Proportion of responses based on Direct co-occurrence (Sentence Completion) and Shared co-occurrence (Label Extension) in Experiments 1–2. Error bars show standard errors of means. Dashed lines depict chance (0 for Sentence Completion; 0.5 for Label Extension)

gradual development of taxonomic versus associative semantic links cannot be explained by the accumulation of experience alone. Given that children and adults were presented with the *same amount of exposure*, and yet differed in the formation of novel semantic links, this pattern favors alternative hypotheses that posit that *abilities* to form semantic links from co-occurrence undergo maturation.

The Introduction noted two maturational possibilities that can explain the results of Experiment 1. The first possibility is that only abilities to form links based on direct co-occurrence improve with development (Arciuli & Simpson, 2011; Raviv & Arnon, 2018; Shufaniya & Arnon, 2018). According to this possibility, the formation of links based on direct co-occurrence collaterally forms links based on shared co-occurrence (Ervin, 1961; McNeill, 1963; Sloutsky et al., 2017). From this perspective, children were worse than adults at forming links based on shared co-occurrence simply due to their weaker

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formation of links based on direct co-occurrence. The second possibility is that the formation of links based on direct co-occurrence may be necessary but insufficient for the formation of links based on shared co-occurrence. Instead, abilities to form links based on shared co-occurrence may also undergo development (Bauer & San Souci, 2010; Schlichting et al., 2017). According to this possibility, children would be worse than adults at forming links based on shared co-occurrence even if they formed robust links based on direct co-occurrence. Experiment 2 was designed to arbitrate between these two maturational possibilities. Specifically, Experiment 2 was designed to strengthen children's formation of direct co-occurrence links to levels similar to the strength of these links in adults in Experiment 1. Experiment 2 accomplished this goal by tripling the amount of training.

EXPERIMENT 2

Method

Participants were twenty-six 4-year-old children (M_{age} = 54.3 months, range 49.2–59.7 months, 16 female) and 32 adults (M_{age} = 18.9 years, range 18.1–21.4 years, 16 female), who did not take part in Experiment 1. An additional six children and three adults failed to complete the study. Power analyses using the effect sizes of developmental differences in Experiment 1 (ds > 1.15) suggested that sample size of 12 participants per age group would be sufficient to detect the same effect sizes with 80% power (α = .05, two-tail). Participants were trained using the same materials and procedures described for Experiment 1, with the exception that the amount of training was tripled.

For 4-year-olds, the three training sessions were distributed over the course of 3 days within 1 week. Children performed the Sentence Completion task after training on each day, and Label Extension on the third day. Adults were trained and tested in the same order but completed all parts within an hour visit to the laboratory.

Results

Sentence completion

Preliminary analyses

Following the same approach as in Experiment 1, we first calculated the proportion of valid responses (i.e., responses using Triad words). Average rates of valid responses were 89.6%, in children and 90.3% in adults.

Main analyses: Formation of direct and shared links

As in Experiment 1, we first computed the proportions of Direct and Shared responses corrected for guessing. To test whether the increased training in Experiment 2 improved the formation of direct co-occurrence links we performed a two-way mixed ANOVA with Training block (within subjects; one vs. two vs. three) and Age (between subjects; 4-year-olds vs. adults) as factors and Direct responses as the dependent variable. The degrees of freedom for the within-subjects comparisons were corrected for violation of sphericity (Greenhouse–Geisser). This analysis revealed that increased training improved the proportions of Direct responses in both age groups, $F(2.98, 166.95) = 16.19$, $p < .001$, $\eta^2_G = .058$ (Figure S1). In addition, adults performed better than children, $F(1, 56) = 7.55$, $p < .01$, $\eta^2_G = .096$. The two factors did not significantly interact ($p > .10$).

In contrast, the same analysis applied to Shared responses revealed no significant effects (Figure S2). The proportion of Shared responses in both children and adults was overall low and did not improve with training (all ps > .05). As noted for Experiment 1, the very low overall rates of Shared responses may be a side-effect of the fact that Sentence Completion assesses only participants' dominant responses.

We next compared Direct and Shared responses in children and adults overall, collapsed across Training blocks. As shown in Figure 5, both children and adults demonstrated above-chance rates of Direct responses (children: $M = .53$, $SD = .23$; adults: $M = .73$, $SD = .30$), one sample ts > 11.66, ps < .001, ds > 2.28, with adults outperforming children, $t(56) = 2.75$, $p < .01$, $d = 0.725$. In the same task, both children and adults showed very low, but above-chance rates of Shared responses (children: $M = .05$, $SD = .07$; adults: $M = .05$, $SD = .07$), one sample ts > 3.50, ps < .01, ds > 0.70, with no significant age differences, $t(56) = 0.18$, $p = .857$, $d = 0.047$.

Label extension

Using the same criteria as in Experiment 1, we excluded six adults (and no children) with accuracy below .25. Replicating results of Experiment 1, we found significant developmental differences in the formation of links based on shared co-occurrence. A mixed effects logistic regression with a fixed effect of Age (levels: 4-year-old and Adult) and random intercepts for participants and stimuli, revealed a significant effect of Age, $\chi^2(1) = 33.97$, $p < .001$. The majority of adults (81%) and only 27% of children performed above chance (ts > 2.40, ps < .048).

Drivers of the formation of shared co-occurrence links

The preceding analyses found developmental changes in the formation of links based on direct and shared co-occurrence, with the formation of shared co-occurrence links lagging substantially behind the formation of direct co-occurrence links. Here, we conducted an analysis to distinguish between two maturational explanations of these patterns: (1) The formation of links based on shared

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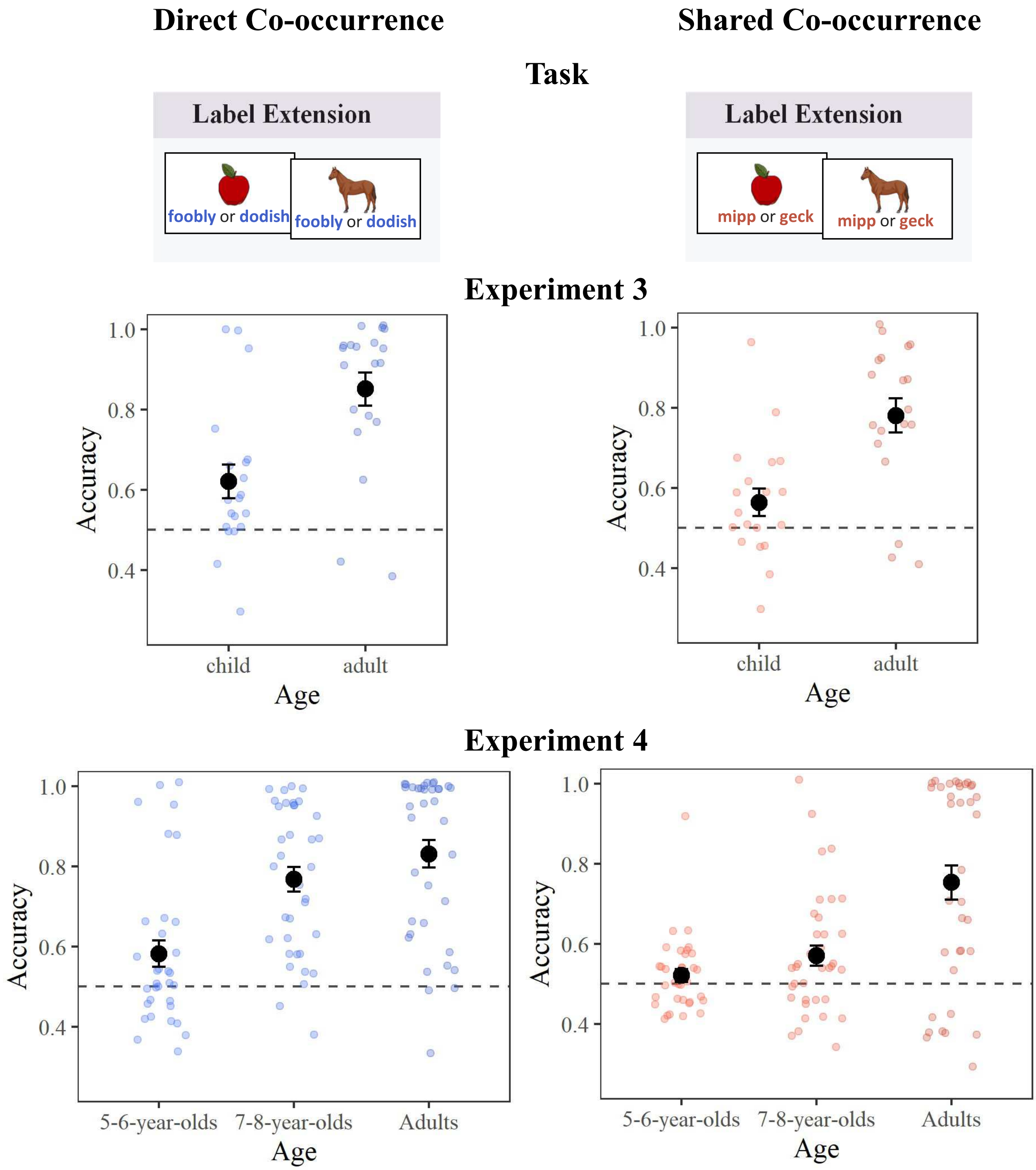

FIGURE 5 Proportion of responses based on Direct and Shared co-occurrence in the Label Extension task in Experiments 3–4. Error bars show standard errors of means. Dashed lines depict chance performance of 0.5

co-occurrence may depend only on the robustness of direct co-occurrence links, or (2) Robust direct co-occurrence links may be necessary but insufficient to form links based on shared co-occurrence, because the formation of these links requires an additional ability that follows its own maturational trajectory. Specifically, this analysis tested whether the formation of shared co-occurrence links was predicted only by direct co-occurrence links (measured from Sentence Completion), or also by age.

Hierarchical regression analyses showed that the strength of the direct co-occurrence links explained a significant amount (34%) of variance in shared co-occurrence-based responses in the Label Extension task, $F(1, 48) = 26.58$, $p < .001$. Importantly, introducing the Age explained additional 27% of variance (change in R^2: $F(1, 47) = 34.11$, $p < .001$). This pattern provides evidence that the formation of shared co-occurrence links depends not only on the robustness of direct co-occurrence

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links, but also on its own maturational trajectory, as evidenced by age effects.

Discussion

Replicating the results of Experiment 1, we found significant developmental differences in the formation of links from both direct and shared co-occurrence regularities. Critically, although 4-year-olds formed strong direct co-occurrence links with extensive training, the majority of them nonetheless failed to form shared co-occurrence links. In contrast, adults successfully formed links based on both direct and shared co-occurrence. Moreover, age predicted the formation of shared co-occurrence links beyond the strength of direct co-occurrence links. These results suggest that abilities to form links based on direct and shared co-occurrence both undergo maturation, with abilities to form links based on shared co-occurrence maturing more slowly than abilities to form links based on direct co-occurrence.

The role of maturation in abilities to form shared co-occurrence links is further highlighted by a comparison between adults in Experiment 1 and children in Experiment 2. Specifically, the strength of direct co-occurrence links was equivalent in adults given short training in Experiment 1 (M = .47, SD = .29) and children given extensive training in Experiment 2 (M = .53, SD = .23); $t(52) = 0.82$, $p = .418$, $d = 0.222$. Thus, even with equally strong direct co-occurrence links, adults formed shared co-occurrence links more successfully than children, $t(52) = 2.89$, $p < .01$, $d = 0.788$.

However, it is critical to note an alternative interpretation. Specifically, different tasks were used to assess the formation of links based on direct and shared co-occurrence. Moreover, the task used to assess the formation of links based on shared co-occurrence may have been more challenging for children due to factors unrelated to abilities to form these links. Such factors may therefore explain the apparent evidence for a gradually developing ability to form links based on shared co-occurrence. To address this issue, in Experiment 3, we measured both direct and shared co-occurrence links using the same Label Extension paradigm.

EXPERIMENT 3

Method

Participants

Participants were twenty 4-to-5-year-olds (M_{age} = 54.1 months, range 48.7–67.2 months, 9 female) and 20 adults recruited from the same population as Experiments 1–2. Based on power analyses using the effect sizes obtained in Experiments 1–2 for testing the formation of direct co-occurrence links in children (ds>1.01), a minimum sample of 10 participants per age group would be sufficient to detect the same effect sizes with 80% power using a paired t test with alpha at .05. To account for the differences in experimental design (i.e., using Label Extension vs. Sentence Completion to assess direct co-occurrence links), we recruited 20 participants per age group.

Stimuli and procedure

Stimuli were the same as in Experiments 1 and 2. The Training procedure was the same as in Experiment 1, with the exception that instead of two, we used three training stories. The Sentence Completion task was included to maintain comparability with the preceding experiments, but not analyzed, because the purpose of this experiment was to measure the formation of links from Label Extension.

The primary feature of Experiment 3 was that the Label Extension task was expanded to measure both direct and shared co-occurrence links (see Figure 5). As in Experiments 1 and 2, on each trial, participants were presented with a picture of a fruit or a mammal and asked to label it using one of two pseudowords from the Triads. Half of the 48 trials measured shared co-occurrence links using the same approach as in Experiments 1 and 2, and they prompted participants to label pictures using one of the two pseudonouns (see Figure 5). Thus, shared co-occurrence links were measured based on consistently labeling fruits with the pseudonoun *mipp* that shared co-occurrence with *apple* and mammals with the pseudonoun *geck* that shared co-occurrence with *horse*. The remaining trials used the same logic to measure direct co-occurrence links by asking participants to label the picture using one of the two pseudoadjectives: *foobly* or *dodish*.

Results

One child and one adult were excluded due to accuracy below .25. Both children and adults made label extensions based on direct co-occurrence links at rates above chance (one sample t-tests against chance, ts>2.91, ps < .05). A mixed effects logistic regression with a fixed effect of Age (levels: 4-year-old and Adult) and random intercepts for participants and stimuli revealed that adults outperformed children, $\chi^2(1) = 10.29$, $p < .01$.

On trials that measured shared co-occurrence links, while adults performed above chance $t(18) = 6.62$, $p < .001$, $d = 1.520$, $M = .78$, $SD = .18$, children were at chance $t(18) = 1.85$, $p = .16$, $d = 0.424$, $M = .56$, $SD = .15$. In addition, a mixed effects logistic regression with a fixed effect of Age (levels: 4-year-old and Adult) and random intercepts for participants revealed that adults made more accurate label extensions based on shared

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co-occurrence than children, $\chi^2(1) = 13.52$, $p < .001$. Similar to Experiment 2, 85% of adults and only 32% of children labeled on the basis of shared co-occurrence.

We conducted an additional analysis to address the possibility that above- versus at-chance performance on direct versus shared co-occurrence trials occurred because it is natural to use adjectives to label a variety of fruits or mammals, whereas nouns typically refer to a specific item. Specifically, we tested whether performance differed across trials in which participants labeled just apples or horses, versus other fruit and other mammal trials. Patterns were equivalent across these trial types (all $Fs < 0.32$, $ps > .57$, Figure S3).

Drivers of the formation of shared co-occurrence links

As in Experiment 2, we performed a hierarchical regression analysis to test whether the formation of links based on shared co-occurrence depended only on the strength of direct co-occurrence links or there was an additional Age effect. The strength of direct co-occurrence links explained a significant amount (45%) of variance in the formation of shared co-occurrence links, $F(1, 33) = 28.49$, $p < .001$. An additional 13% of variance was explained by Age. The addition of Age as a predictor significantly improved the model, $F(1, 32) = 10.24$, $p = .003$.

Discussion

The results of Experiment 3 replicated and extended findings of the preceding experiments. First, the ability to form links based on direct co-occurrence was present in both children and adults, but it improved with development. Second, only adults consistently formed links based on shared co-occurrence. Similarly, age contributed to predicting the formation of shared co-occurrence links beyond the strength of direct co-occurrence links. Together, these results support the Co-Occurrence Account's attribution of the more gradual development of taxonomic links to the asynchronous development of abilities to form links based on direct and shared co-occurrence.

It is important to note that the use of the same task to assess links based on both direct and shared co-occurrence undermines the possibility that their apparently different developmental trajectories are due to task differences. However, it is worth acknowledging that developmental differences in this experiment were modest, with 4-year-olds performing slightly but significantly above-chance for direct co-occurrence links, and at chance for shared co-occurrence links. Experiment 4 was therefore designed to further investigate the developmental asynchrony between abilities to form links based on direct versus shared co-occurrence. Specifically, if the developmental patterns capture a true developmental asynchrony, then abilities to form shared co-occurrence links should lag behind abilities to form direct co-occurrence links, *even as both abilities improve with age*. We tested this assumption in Experiment 4 by investigating the trajectory of improvements across three age groups: 5- to 6-year-olds, 7- to 8-year-olds, and adults.

EXPERIMENT 4

Method

Participants

Participants were thirty-four 5-to-6-year-old children ($M_{age} = 70.0$ months, range 60.6–80.5 months, 19 female), thirty-six 7- to 8-year-old children ($M_{age} = 93.2$ months, range 84.3–105.4 months, 22 female) and 36 adults. Child participants were recruited from the same population as for Experiments 1–3. Adult participants were either undergraduate students ($N = 19$, same population as in Experiments 1–3) or recruited through Prolific platform ($N = 17$, https://www.prolific.co).

It is worth noting that this experiment was conducted during the COVID-19 pandemic. While conducting research during the pandemic, we observed that both children and adults appeared to find it more challenging to participate attentively in experiments. Motivated by this observation, to increase power, we collected larger sample sizes than in previous experiments.

Stimuli

Stimuli were adapted from Experiments 1–3, with two minor adjustments. First, Training sentences were modified so that they formed "mini stories" consisting of four sentences, one for each of the word pairs from the two triads. This modification was designed to ensure that sentences flowed sensibly from one sentence to the next (see Supporting Information for the full list of sentences). Second, the Label Extension task used only trials in which participants labeled images of apples or horses. The aim was to provide an explicit assessment of the *formation* of links between familiar and pseudowords, and thus eliminate the demand to *generalize* pseudowords to the broader semantic categories to which the familiar words belonged (i.e., fruits and animals).

Procedure

As in the preceding experiments, participants completed Training, Sentence Completion, and Label Extension tasks. The Training phase was slightly modified from preceding experiments so that participants clicked a colored

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circle on the computer screen to hear each "mini story" of four sentences. As in Experiment 1, Training included two blocks of training stories. The Label Extension task was similar to Experiment 3, with the exception that all 48 trials prompted participants to label an image of an apple or a horse, rather than other fruits or mammals.

Results

All participants passed the accuracy threshold of 0.25. Although all age groups performed above chance on direct co-occurrence trials, all ts>2.52, ps<.034, there were significant developmental differences as confirmed by a mixed effects logistic regression with a fixed effect of Age (levels: 5- to 6-year-old, 7- to 8-year-old and Adult) and random intercepts for participants, $\chi^2(2) = 25.12$, $p<.001$. Pairwise comparisons using Z-tests, corrected with Holm's sequential Bonferroni procedure revealed that 7-to-8-year-olds performed significantly better than 5- to 6-year-olds, $Z = 3.12$, $p<.01$, and significantly worse than adults, $Z = 2.14$, $p = .032$.

On shared co-occurrence trials, 5- to 6-year-olds performed at chance, $t(33) = 1.29$, $p = .412$, $d = 0.221$, 7- to 8-year-olds were just above the chance $t(35) = 2.78$, $p = .018$, $d = 0.463$, and adults performed substantially above chance, $t(35) = 5.93$, $p<.001$, $d = 0.988$. Mixed effects logistic regression with a fixed effect of Age (levels: 5- to 6-year-olds, 7- to 8-year-olds, and Adult) and random intercepts for participants revealed significant developmental differences, $\chi^2(2) = 32.89$, $p<.001$. Pairwise comparisons using Z-tests, corrected with Holm's sequential Bonferroni procedure, indicated that while adults made more correct responses than 5- to 6-year-olds and 7- to 8-year-olds, Zs>4.64, ps<.001, there were no differences in performance of 5- to 6-year-olds and 7- to 8-year-olds, $Z = 0.96$, $p = .336$.

This pattern replicates the developmental patterns observed in young children and adults in Experiment 3. Critically, older children (7- to 8-year-olds) provide crucial additional information: although they formed direct-co-occurrence links that were robust and substantially stronger than younger children, formation of shared co-occurrence links remained weak (Figure 5). Moreover, 7- to 8-year-olds formed direct co-occurrence links significantly more successfully than shared co-occurrence links according to performance on the same task, $t(35) = 5.38$, $p<.001$, $d = 1.157$. These results strengthen the conclusions from Experiments 1–3 that abilities to form semantic links from direct and shared co-occurrence regularities follow different developmental trajectories.

Drivers of the formation of shared co-occurrence links

As in previous experiments, we performed a hierarchical regression analysis to test whether Age contributes to explaining the formation of shared co-occurrence links beyond the strength of direct co-occurrence links. Replicating the results of the Experiments 2–3, we found that in addition to the significant amount (18%) of variance explained by the strength of direct co-occurrence links, $F(1, 104) = 23.66$, $p<.001$, including Age as a predictor significantly improved the model, $F(2, 102) = 9.26$, $p<.001$, and explained an additional 13% of variance. Therefore, the current experiment fully replicates the patterns observed in Experiments 2–3 and further strengthens the argument that formation of shared co-occurrence links depends on both strength of direct links and an independent maturation of mechanisms necessary to form shared co-occurrence links.

GENERAL DISCUSSION

Words tend to occur in language in predictable ways. Associatively related words, such as *juicy* and *apple*, tend to reliably directly co-occur, while words that are taxonomically related, such as *apple* and *pear*, tend to share each other's patterns of direct co-occurrence. For example, both *apple* and *pear* directly co-occur with words such as *juicy* or *eat* (Harris, 1954; Landauer & Dumais, 1997; Lund & Burgess, 1996; Miller & Charles, 1991). These regularities are abundant even in linguistic input to young children (Asr et al., 2016; Fourtassi, 2020; Huebner & Willits, 2018), and therefore represent a potentially powerful driver of semantic organization development. The present study investigated how abilities to form semantic links based on co-occurrence regularities emerge during development, and how these developing abilities may drive developmental changes in semantic organization.

Across four experiments, we observed that abilities to form links based on direct co-occurrence emerged early and became more robust by adulthood (see Shufaniya & Arnon, 2018; Wojcik & Saffran, 2015 for converging evidence in language and other domains). In contrast, the formation of links based on shared co-occurrence was weak in children, and robust only in adults (see Miller-Goldwater et al., 2021; Schlichting et al., 2021 for converging evidence in other domains). Moreover, the formation of links based on shared co-occurrence was predicted by both the strength of direct co-occurrence-based links, and by an independent contribution of age. These results suggest that the formation of links based on direct and shared co-occurrence depends on abilities that develop asynchronously, with the development of abilities to form links based on shared co-occurrence lagging behind abilities to form links based on direct co-occurrence.

These findings provide a novel explanation for the development of semantic organization, in which associative links emerge early and are gradually supplemented by taxonomic links. First, associative links may emerge early because they can be learned via early-developing

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abilities to form links based on direct co-occurrence. Second, the relatively slow emergence of taxonomic links can be explained by the more gradual development of the ability to form shared co-occurrence links. These findings thus highlight an alternative to the common view that associative and taxonomic links develop independently. According to this new perspective, associative links not only play a key role in semantic organization throughout development (Blaye et al., 2006; Fenson et al., 1989; Lin & Murphy, 2001; Sloutsky et al., 2017; Unger, Savic, et al., 2020), but moreover can provide a foundation for developing taxonomic links (Sloutsky et al., 2017).

It is worth noting that neither the Co-Occurrence account nor the current findings conflict with evidence that links between *some* taxonomically related concepts may emerge early. Such links may form when shared co-occurrence is not the only source of input from which these links can form. For example, the current findings are consistent with recent evidence that links between some taxonomically related concepts emerge early when their labels *directly* co-occur, such as "dog" and "cat" (Unger, Vales, et al., 2020; Yim et al., 2021). In addition, as noted in the Introduction, concepts may become taxonomically linked relatively early in development when their real-world counterparts share many observable features.

Similarly, the present work complements evidence that there are other useful cues in language that can support learning semantic links between words. For example, Wojcik and Saffran (2015) demonstrated that toddlers can learn that words are related when they occur in similar positions and have same syntactic roles in different sentences, such as occurring early in a sentence as the subject of transitive verbs or late in a sentence as the object of transitive verbs. Given this evidence, in the current work, we intentionally controlled for the contribution of these cues to demonstrate that learning is possible even when word co-occurrences provide the only cues to word meaning. Therefore, the current findings provide evidence that co-occurrence regularities may make an independent contribution to the development of semantic organization.

Although the converging evidence found across a set of experiments in the current study provides support for the generalizability of the current findings, it is important to keep in mind that all children recruited for this study were English native speakers living in middle-class suburbs of a U.S. city. Therefore, caution is necessary when generalizing the current findings to different sociocultural groups with different learning backgrounds and environments. Specifically, it is possible that the development of abilities related to learning from co-occurrence may be supported by a child's level of language comprehension, vocabulary size, and exposure to language, which are known to vary across different sociocultural groups. Additionally, we cannot confirm that our findings can be generalized cross-linguistically. Due to variations in syntactic properties, languages tend to have different distributional regularities, which could influence how much children rely on co-occurrence in language when learning about semantic relatedness. Therefore, future work would need to investigate potential cross-cultural and cross-linguistic differences in the contribution of word co-occurrences to semantic development.

Roles of experience and maturation

Our findings further contribute to understanding the roles that experience and maturation play in the development of semantic organization. While exposure to co-occurrence regularities is obviously critical for forming links based on co-occurrence regularities, our findings strongly suggest that accumulation of experience alone cannot fully explain developmental changes. Specifically, we found developmental differences in the formation of co-occurrence-based links even though children and adults in our experiments were given the *same amount of exposure* to co-occurrence regularities. The role of maturation is further highlighted by a comparison of the performance of adults given short training (Experiment 1) and children given extensive training (Experiment 2). With extensive training, direct co-occurrence links in children became as strong as direct co-occurrence links in adults who were given short training. However, extensive training did not strengthen shared co-occurrence links in children. This finding suggests that the formation of robust direct co-occurrence links is necessary but not sufficient for formation of shared co-occurrence links. Instead, learners also need to develop the ability to form links based on shared co-occurrence. Thus, these findings suggest that models that capture human semantic knowledge based on co-occurrence regularities (Jones & Mewhort, 2007; Landauer & Dumais, 1997; Lund & Burgess, 1996; Mikolov et al., 2013) capture an important source of input for developing semantic knowledge, but overlook key developmental changes in abilities to learn from this input.

Finally, it is important to note that the reported developmental differences likely capture the development of abilities to form semantic links from co-occurrence regularities, rather than the development of reasoning abilities that could aid performance in the tasks used here. The strongest evidence for this interpretation comes from Experiments 3 and 4, which assessed direct and shared co-occurrence links in the same task. Experiment 3 found that even within the same task, young children could form direct co-occurrence links above chance, while remaining at chance for shared co-occurrence links. Experiment 4 expanded upon this evidence by showing that even as the formation of both links improved with age, the stronger formation of links based on direct versus shared co-occurrence persisted and was

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even more pronounced in older children. Thus, developmental differences in reasoning abilities are unlikely to explain the key patterns of development observed across our three experiments.

Learning mechanisms

The evidence for the asynchronous development of abilities to form links from direct and shared co-occurrence highlights a key question for future research: What mechanistic changes drive these asynchronous maturational trajectories? One possible mechanism for the formation of links based on shared co-occurrence involves processes that we refer to as *reactivation* and *co-activation*. Imagine a learner who first hears "foobly apple," and later hears "foobly mipp". When the learner hears "foobly apple," they may encode a direct co-occurrence link between "foobly" and "apple." When the learner then hears "foobly mipp," hearing "foobly" may reactivate "apple," so that "mipp" and "apple" are simultaneously activated. The co-activation of "mipp" and "apple" may then prompt the formation of a shared co-occurrence link between them. Emerging research suggests that both reactivation and the formation of a new memory trace based on co-activation may rely on hippocampal processing that is carried out by hippocampal regions that undergo protracted development (Schlichting et al., 2017). Thus, the development of these processes may account for developmental improvements in abilities to form links based on shared co-occurrence.

Beyond this possibility, multiple alternative mechanistic explanations for the formation of links based on shared co-occurrence have been proposed in a variety of research disciplines. For example, in computational models that capture semantic organization from regularities of word use such as co-occurrence (Borovsky & Elman, 2006; Huebner & Willits, 2018; Landauer & Dumais, 1997; Mikolov et al., 2013), dimensionality reduction processes capture shared co-occurrence as a latent source of these regularities (for similar proposals in the domain of memory, see Schapiro et al., 2013, 2017). In the behaviorist literature, researchers have proposed mediated association mechanisms (Hall, 1996; Hall et al., 2003) in which inputs that share co-occurrence become indirectly linked via their overlapping direct co-occurrence-based links. Alternatively, some memory models (Hintzman, 1984; Kumaran & McClelland, 2012) propose that although only direct co-occurrence links are initially stored in memory, retrieving these links from memory may foster the formation of shared co-occurrence links. For example, after foobly-apple and foobly-mipp have been stored in memory, encountering one of these words—for example, "apple"—can prompt the retrieval of the word with which it directly co-occurred—for example, "foobly." The retrieved word can in turn prompt retrieval of the other word with which *it* directly co-occurred—for example, "mipp." This chained retrieval process would cause the actually encountered word—"apple"—to be co-active with the word with which it shared co-occurrence—"mipp"—which can then form a new memory trace for apple-mipp. This multitude of candidate mechanisms contrasts with a lack of work that has evaluated them as accounts of the development of semantic organization. The mechanistic sources of developmental changes in semantic organization therefore remain an unexplored avenue for future research.

CONCLUSION

With development, we acquire richly organized networks of knowledge in which concepts, denoted by words, are connected by semantic links. The present research illuminates how exposure to simple co-occurrence regularities in language may contribute to the development of this richly organized knowledge. Our findings suggest that the accumulation of exposure to co-occurrence regularities may contribute to the development of semantic organization only in conjunction with the maturation of abilities to form semantic links from this exposure.

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REFERENCES

Arciuli, J., & Simpson, I. C. (2011). Statistical learning in typically developing children: The role of age and speed of stimulus presentation. *Developmental Science*, *14*, 464–473. https://doi.org/10.1111/j.1467-7687.2009.00937.x

Arnon, I., & Snider, N. (2010). More than words: Frequency effects for multi-word phrases. *Journal of Memory and Language*, *62*, 67–82. https://doi.org/10.1016/j.jml.2009.09.005

Asr, F. T., Willits, J. A., & Jones, M. N. (2016). Comparing predictive and co-occurrence based models of lexical semantics trained on child-directed speech. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *38*, 1092–1097. https://cogsci.mindmodeling.org/2016/

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48. https://doi.org/10.48550/arXiv.1406.5823

Bauer, P. J., & San Souci, P. (2010). Going beyond the facts: Young children extend knowledge by integrating episodes. *Journal*

14678624, 2023, 1, Downloaded from https://srcd.onlinelibrary.wiley.com/doi/10.1111/cdev.13844 by Test, Wiley Online Library on [24/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

of Experimental Child Psychology, *107*, 452–465. https://doi.org/10.1016/j.jecp.2010.05.012

Blaye, A., Bernard-Peyron, V., Paour, J.-L., & Bonthoux, F. (2006). Categorical flexibility in children: Distinguishing response flexibility from conceptual flexibility. *European Journal of Developmental Psychology*, *3*, 163–188. https://doi.org/10.1080/17405620500412267

Borovsky, A., & Elman, J. (2006). Language input and semantic categories: A relation between cognition and early word learning. *Journal of Child Language*, *33*, 759–790. https://doi.org/10.1017/S0305000906007574

Coley, J. D. (2012). Where the wild things are: Informal experience and ecological reasoning. *Child Development*, *83*, 992–1006. https://doi.org/10.1111/j.1467-8624.2012.01751.x

Cree, G. S., & Armstrong, B. C. (2012). Computational models of semantic memory. In M. Spivey, M. Joanisse, & K. McRae (Eds.), *The cambridge handbook of psycholinguistics* (pp. 259–282). Cambridge University Press.

Ervin, S. M. (1961). Changes with age in the verbal determinants of word-association. *The American Journal of Psychology*, *74*, 361–372. https://doi.org/10.2307/1419742

Fenson, L., Vella, D., & Kennedy, M. (1989). Children's knowledge of thematic and taxonomic relations at two years of age. *Child Development*, *60*, 911–919. https://doi.org/10.2307/1131032

Fisher, A. V. (2011). Processing of perceptual information is more robust than processing of conceptual information in preschool-age children: Evidence from costs of switching. *Cognition*, *119*, 253–264. https://doi.org/10.1016/j.cognition.2011.01.015

Fourtassi, A. (2020). *Word co-occurrence in child-directed speech predicts children's free word associations*. Paper presented at the Proceedings of the Workshop on Cognitive Modeling and Computational Linguistics.

Gentner, D., & Namy, L. L. (1999). Comparison in the development of categories. *Cognitive Development*, *14*, 487–513. https://doi.org/10.1016/S0885-2014(99)00016-7

Gobbo, C., & Chi, M. (1986). How knowledge is structured and used by expert and novice children. *Cognitive Development*, *1*, 221–237. https://doi.org/10.1016/S0885-2014(86)80002-8

Hall, G. (1996). Learning about associatively activated stimulus representations: Implications for acquired equivalence and perceptual learning. *Animal Learning & Behavior*, *24*, 233–255. https://doi.org/10.3758/BF03198973

Hall, G., Mitchell, C., Graham, S., & Lavis, Y. (2003). Acquired equivalence and distinctiveness in human discrimination learning: Evidence for associative mediation. *Journal of Experimental Psychology: General*, *132*, 266–276. https://doi.org/10.1037/0096-3445.132.2.266

Harris, Z. S. (1954). Distributional structure. *Word*, *10*, 146–162. https://doi.org/10.1080/00437956.1954.11659520

Hintzman, D. L. (1984). Minerva 2: A simulation model of human memory. *Behavior Research Methods, Instruments, & Computers*, *16*, 96–101. https://doi.org/10.3758/BF03202365

Hofmann, M. J., Biemann, C., Westbury, C., Murusidze, M., Conrad, M., & Jacobs, A. M. (2018). Simple co-occurrence statistics reproducibly predict association ratings. *Cognitive Science*, *42*, 2287–2312. https://doi.org/10.1111/cogs.12662

Huebner, P. A., & Willits, J. A. (2018). Structured semantic knowledge can emerge automatically from predicting word sequences in child-directed speech. *Frontiers in Psychology*, *9*, 133. https://doi.org/10.3389/fpsyg.2018.00133

Inhelder, B., & Piaget, J. (1964). *The early growth of logic in the child*. Norton.

Jones, M. N., & Mewhort, D. J. (2007). Representing word meaning and order information in a composite holographic lexicon. *Psychological Review*, *114*, 1–37. https://doi.org/10.1037/0033-295X.114.1.1

Jones, M. N., Willits, J., & Dennis, S. (2015). Models of semantic memory. In J. Busemeyer & J. Townsend (Eds.), *Oxford handbook of mathematical and computational psychology* (pp. 232–254). Oxford University Press.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, *83*, B35–B42. https://doi.org/10.1016/S0010-0277(02)00004-5

Kumaran, D., & McClelland, J. L. (2012). Generalization through the recurrent interaction of episodic memories: A model of the hippocampal system. *Psychological Review*, *119*, 573. https://doi.org/10.1037/a0028681

Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, *4*, 463–470. https://doi.org/10.1016/S1364-6613(00)01560-6

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). Lmertest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*, 1–26. https://doi.org/10.18637/jss.v082.i13

Landauer, T. K., & Dumais, S. T. (1997). A solution to plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*, *104*, 211–240. https://doi.org/10.1037/0033-295X.104.2.211

Lewis, M., Zettersten, M., & Lupyan, G. (2019). Distributional semantics as a source of visual knowledge. *Proceedings of the National Academy of Sciences of the United States of America*, *116*, 19237–19238. https://doi.org/10.1073/pnas.1910148116

Lin, E. L., & Murphy, G. L. (2001). Thematic relations in adults' concepts. *Journal of Experimental Psychology: General*, *130*, 3–28. https://doi.org/10.1037/0096-3445.130.1.3

López, A., Gelman, S. A., Gutheil, G., & Smith, E. E. (1992). The development of category-based induction. *Child Development*, *63*, 1070–1090. https://doi.org/10.1111/j.1467-8624.1992.tb01681.x

Lucariello, J., Kyratzis, A., & Nelson, K. (1992). Taxonomic knowledge: What kind and when? *Child Development*, *63*, 978–998. https://doi.org/10.1111/j.1467-8624.1992.tb01676.x

Lucariello, J., & Nelson, K. (1985). Slot-filler categories as memory organizers for young children. *Developmental Psychology*, *21*, 272–282. https://doi.org/10.1037/0012-1649.21.2.272

Lucas, M. (2000). Semantic priming without association: A meta-analytic review. *Psychonomic Bulletin & Review*, *7*, 618–630. https://doi.org/10.3758/BF03212999

Lund, K., & Burgess, C. (1996). Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, & Computers*, *28*, 203–208. https://doi.org/10.3758/BF03204766

McClelland, J. L., & Rogers, T. T. (2003). The parallel distributed processing approach to semantic cognition. *Nature Reviews Neuroscience*, *4*, 310–322. https://doi.org/10.1038/nrn1076

McDonald, S. A., & Shillcock, R. C. (2003). Eye movements reveal the on-line computation of lexical probabilities during reading. *Psychological Science*, *14*, 648–652. https://doi.org/10.1046/j.0956-7976.2003.psci_1480.x

McNeill, D. (1963). The origin of associations within the same grammatical class. *Journal of Verbal Learning and Verbal Behavior*, *2*, 250–262. https://doi.org/10.1016/S0022-5371(63)80091-2

McNeill, D. (1966). A study of word association. *Journal of Memory and Language*, *5*, 548–557. https://doi.org/10.1016/S0022-5371(66)80090-7

Mikolov, T., Chen, K., Corrado, G., & Dean, J. (2013). Efficient estimation of word representations in vector space. *arXiv preprint arXiv:1301.3781*. https://doi.org/10.48550/arXiv.1301.3781

Miller, G. A., & Charles, W. G. (1991). Contextual correlates of semantic similarity. *Language and Cognitive Processes*, *6*, 1–28. https://doi.org/10.1080/01690969108406936

Miller-Goldwater, H. E., Cronin-Golomb, L. M., Porter, B. M., & Bauer, P. J. (2021). Developmental differences in reactivation underlying self-derivation of new knowledge through memory integration. *Cognitive Psychology*, *129*, 101413. https://doi.org/10.1016/j.cogpsych.2021.101413

14678624, 2023, 1, Downloaded from https://srcd.onlinelibrary.wiley.com/doi/10.1111/cdev.13844 by Test, Wiley Online Library on [24/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Nelson, K. (1977). The syntagmatic-paradigmatic shift revisited: A review of research and theory. *Psychological Bulletin*, *84*, 93–116. https://doi.org/10.1037/0033-2909.84.1.93

Osherson, D. N., Smith, E. E., Wilkie, O., Lopez, A., & Shafir, E. (1990). Category-based induction. *Psychological Review*, *97*, 185–200. https://doi.org/10.1037/0033-295X.97.2.185

Quinn, P. C., & Eimas, P. D. (1997). A reexamination of the perceptual-to-conceptual shift in mental representations. *Review of General Psychology*, *1*, 271–287. https://doi.org/10.1037/1089-2680.1.3.271

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Raviv, L., & Arnon, I. (2018). The developmental trajectory of children's auditory and visual statistical learning abilities: Modality-based differences in the effect of age. *Developmental Science*, *21*, e12593. https://doi.org/10.1111/desc.12593

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology*, *8*, 382–439. https://doi.org/10.1016/0010-0285(76)90013-X

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, *70*, 27–52. https://doi.org/10.1016/S0010-0277(98)00075-4

Schapiro, A. C., Rogers, T. T., Cordova, N. I., Turk-Browne, N. B., & Botvinick, M. M. (2013). Neural representations of events arise from temporal community structure. *Nature Neuroscience*, *16*, 486–492. https://doi.org/10.1038/nn.3331

Schapiro, A. C., Turk-Browne, N. B., Botvinick, M. M., & Norman, K. A. (2017). Complementary learning systems within the hippocampus: A neural network modelling approach to reconciling episodic memory with statistical learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*, 20160049. https://doi.org/10.1098/rstb.2016.0049

Schlichting, M. L., Guarino, K. F., Roome, H. E., & Preston, A. R. (2021). Developmental differences in memory reactivation relate to encoding and inference in the human brain. *Nature Human Behaviour*, *6*, 415–428. https://doi.org/10.1038/s41562-021-01206-5

Schlichting, M. L., Guarino, K. F., Schapiro, A. C., Turk-Browne, N. B., & Preston, A. R. (2017). Hippocampal structure predicts statistical learning and associative inference abilities during development. *Journal of Cognitive Neuroscience*, *29*, 37–51. https://doi.org/10.1162/jocn_a_01028

Shufaniya, A., & Arnon, I. (2018). Statistical learning is not age-invariant during childhood: Performance improves with age across modality. *Cognitive Science*, *42*, 3100–3115. https://doi.org/10.1111/cogs.12692

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. (2022). Afex: Analysis of factorial experiments. R package version 1.1-1. https://CRAN.R-project.org/package=afex

Sloutsky, V. M. (2010). From perceptual categories to concepts: What develops? *Cognitive Science*, *34*, 1244–1286. https://doi.org/10.1111/j.1551-6709.2010.01129.x

Sloutsky, V. M., Yim, H., Yao, X., & Dennis, S. (2017). An associative account of the development of word learning. *Cognitive Psychology*, *97*, 1–30. https://doi.org/10.1016/j.cogpsych.2017.06.001

Unger, L., & Fisher, A. V. (2019). Rapid, experience-related changes in the organization of children's semantic knowledge. *Journal of Experimental Child Psychology*, *179*, 1–22. https://doi.org/10.1016/j.jecp.2018.10.007

Unger, L., Savic, O., & Sloutsky, V. M. (2020). Statistical regularities shape semantic organization throughout development. *Cognition*, *198*, 104190. https://doi.org/10.1016/j.cognition.2020.104190

Unger, L., Vales, C., & Fisher, A. (2020). The role of co-occurrence statistics in developing semantic knowledge. *Cognitive Science*, *44*, e12894. https://doi.org/10.1111/cogs.12894

Vales, C., States, S. L., & Fisher, A. V. (2020). Experience-driven semantic differentiation: Effects of a naturalistic experience on within-and across-domain differentiation in children. *Child Development*, *91*, 733–742. https://doi.org/10.1111/cdev.13369

Wojcik, E. H., & Kandhadai, P. (2019). Paradigmatic associations and individual variability in early lexical–semantic networks: Evidence from a free association task. *Developmental Psychology*, *56*, 53–69. https://doi.org/10.1037/dev0000844

Wojcik, E. H., & Saffran, J. R. (2015). Toddlers encode similarities among novel words from meaningful sentences. *Cognition*, *138*, 10–20. https://doi.org/10.1016/j.cognition.2015.01.015

Yim, H., Savic, O., Barkhimer, A., Sloutsky, V., & Dennis, S. (2021). The mystery of early taxonomic development. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. *43*, pp. 3103–3108). Cognitive Science Society. https://escholarship.org/uc/item/4nz77271

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