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RESEARCH ARTICLE

Tracking the associative boost in infancy

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Abstract

Do words that are both associatively and taxonomically related prime each other in the infant mental lexicon? We explore the impact of these semantic relations in the emerging lexicon. Using the head-turn preference procedure, we show that 18-month-old infants have begun to construct a semantic network of associatively and taxonomically related words, such as dog-cat or apple-cheese. We demonstrate that priming between words is longer-lasting when the relationship is both taxonomic and associative, as opposed to purely taxonomic, reflecting the *associative boost* reported in the adult priming literature. Our results demonstrate that 18-month-old infants are able to construct a lexical-semantic network based on associative and taxonomic relations between words in the network, and that lexical-semantic links are more robust when they are *both* associative *and* taxonomic in character. Furthermore, the manner in which activation is propagated through the emerging lexical-semantic network appears to depend upon the type of semantic relation between words. We argue that 18-month-old infants have a mental lexicon that shares important structural and processing properties with that of the adult system.

1 | INTRODUCTION

Infants assign meaning to words as early as 6 months of age (Bergelson & Swingley, 2012; Friedrich & Friederici, 2017; Tincoff & Jusczyk, 1999) then slowly accrue word knowledge until their second year of life, at which point vocabulary development accelerates notably (McMurray, 2007; McShane, 1979). Very early word learning can be accounted for by general associative learning capacities similar to those found in other species (Gardner & Gardner, 1969; Kaminski et al., 2004; Pepperberg, 1981). But words in the mature human mind are not mere associations between a sound and an object or a concept (Bloom, 2004). They carry a rich representational structure, constitute core elements of higher-level grammatical structures (Elman, 2009), and in the mental lexicon they are connected through a complex network of semantic relationships (Gaskell & Marslen-Wilson, 2002). How humans build up this complex structure during infancy has remained mostly unknown until recently.

Meaning relations between words, sometimes called semantic links, can be associative, thematic, or taxonomic (see Figure 1). Associative links between words, such as *pillar* and *society,* are thought to derive from their frequent co-occurrence in utterances (Fischler, 1977; Shelton & Martin, 1992). Under such circumstances, the relationship between words may be purely lexical (Moss et al., 1995). However, co-occurrence of words in utterances may also derive from their referents sharing a complementary relationship in time or space, such as *dog* and *bone*, in which case the words may also be considered thematically linked. Taxonomic relations refer to higher-order category links such as the taxonomy of mammals that relates *dog* and *cow,* which often share perceptual and/or functional features (*four-legged*, *is-alive*). Thematic/associative and taxonomic relationships between words are thought to recruit distinct neural architectures in adults, indicating that they are functionally dissociable in the brain (Lewis et al., 2015; Schwartz et al., 2011; Simoes Loureiro & Lefebvre, 2016). Eye-tracking studies using the visual world paradigm have also demonstrated a differentiation of taxonomic and thematic preferences, supporting the assertion that separable mechanisms underpin taxonomic and associative/thematic processing in the adult brain (Mirman & Graziano, 2012).

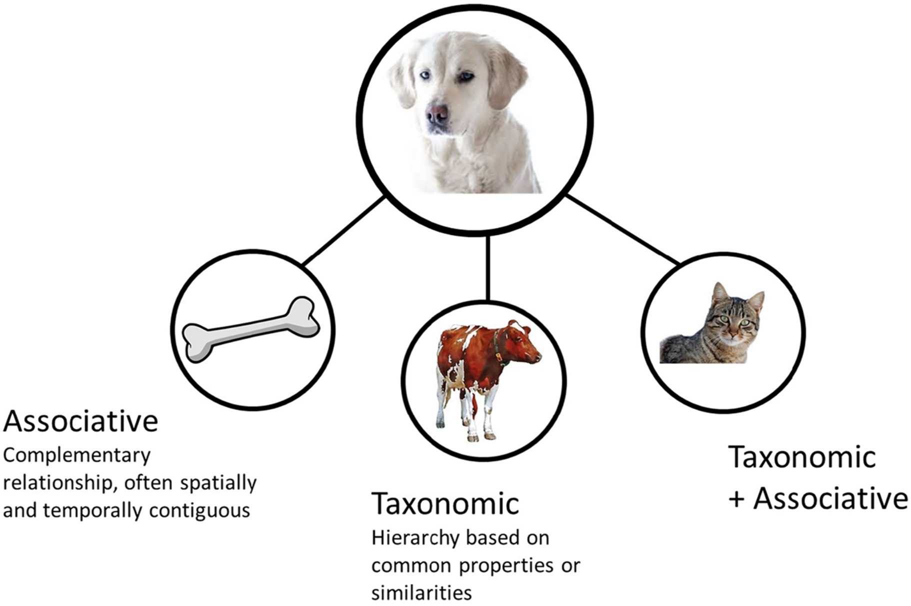

FIGURE 1 Illustration of taxonomic and associative links between concepts or words

Semantically related words are known to prime each other in adulthood, typically indexed by speeded response times or improved accuracy in a lexical decision task (Meyer & Schvaneveldt, 1971). These priming effects are interpreted as a key source of evidence for inferring the existence and character of a structured mental lexicon in adults. The strength and duration of semantic priming in adults differs according to the type of link between words in the adult lexicon. Associative/thematic priming is generally strong and long lasting (>600 ms) whereas taxonomic priming is relatively weak and short-lived (<400 ms) (McNamara, 2005; Murphy & Hunt, 2013; Seidenberg et al., 1984). For example, *dog* primes *bone* robustly, sometimes across intervening items, whereas priming of *pig* by *dog* does not survive such interference (Joordens & Besner, 1992). Semantic priming is strongest when words are *both* taxonomically and associatively/thematically related—the *associative boost* effect (Moss et al., 1995; Shelton & Martin, 1992). For example, *cat* primes *dog* more strongly than *cat* primes *rabbit*.

Distributed network models that implement the associative/taxonomic processing distinction capture a broad range of experimental and neuropsychological findings and offer converging evidence for the theoretical foundations of this distinction (Moss et al., 1994; Plaut, 1995). For example, Plaut and Booth (2000) suggest that taxonomic priming is best explained by semantic feature overlap between prime and target items in a distributed network model, whereas associative priming occurs as a result of the frequent co-occurrence of words during learning. According to Plaut and Booth (2000), the short-lived character of taxonomic priming is explained in terms of hysteresis effects in moving from one stable state of the network to another: once the feature set of the prime is fully activated, the transition to the feature set of the target will benefit from the features it has in common with the prime but will also be inhibited by the features that differ. At short stimulus onset asynchronies (SOAs), nonoverlapping features are not fully activated. Hence, overlapping features prime the transition to the target. At long SOAs (around 800 ms), nonoverlapping features of the prime are fully active and can inhibit the transition to the target (Plaut, 1995; Plaut & Booth, 2000). No such inhibitory effects emerge with associative priming because associative priming does not depend on feature overlap. Facilitative associative priming occurs through direct connections between lexical forms or derives from their referents sharing a complementary relationship in time or space. Other distributed network models of semantic priming implement synaptic depression mechanisms to capture SOA effects (Huber & O'Reilly, 2003; Lerner et al., 2012).

There is a substantial body of evidence stating that children are sensitive to the taxonomic and associative relations between words in their vocabularies. For example, Schvaneveldt et al. (1977) showed that semantic context influences written word recognition in a lexical decision task: 7.6- and 9.5-year-olds were faster and more accurate at reading pairs of associated written words than nonassociated words; Nation and Snowling (1999) found that both functionally (episodic/thematic) related words and category (taxonomic/semantic) related words primed 10-year-old normal and poor readers' reaction times in an auditory lexical decision task; category priming was obtained for normal readers even when prime-target word pairs had low associative strength. However, category priming was obtained with poor readers only if the prime-target word pairs shared high association strength, indicating that poor readers may be less sensitive to abstract semantic relations than normal readers. McCauley et al. (1976) reported that 8-year-olds showed facilitation for both thematically and taxonomically related pairs in a picture naming task, while 6-year-olds' target naming was faster when a prime picture and a target picture were thematically related as opposed to taxonomically related. More recently, Unger et al. (2020) showed that 4–5-year-olds are sensitive to co-occurrence (associative) relations between words in both cued-recall and picture matching tasks, but failed to find sensitivity to taxonomic relations in these tasks with the same participants. However, these authors found weak evidence for sensitivity to taxonomic relatedness in a preferential looking task with a similar age group, albeit much weaker than the children's sensitivity to co-occurrence relations. These investigations demonstrate children's sensitivity to both thematic and taxonomic relationships between pairs of objects, pictures, or words, though they tend to point to an early advantage for associative/functional/episodic/thematic relationships over purely semantic/taxonomic ones, though it is worth keeping in mind that some studies have argued that children favor taxonomic relations over associative relations (Markman & Hutchinson, 1984; Xu & Tenenbaum, 2007).

A growing body of evidence indicates that even infants and toddlers are sensitive to semantic relations between words in their vocabularies. In an intermodal preferential looking task, Arias-Trejo and Plunkett (2009) showed that 21-month-olds will look longer and orient faster to a target picture when it is preceded by a pair of semantically related words (e.g., *cat–dog*) than when preceded by a pair of semantically unrelated words (e.g., *plate–dog*). Similar results have been reported for monolingual toddlers (Jardak & Byers-Heinlein, 2018; Styles & Plunkett, 2009) and cross-language semantic priming in bilingual toddlers (Floccia et al., 2020; Jardak & Byers-Heinlein, 2018; Singh, 2014) using the same type of task. However, all these studies used related word pairs that were *both* taxonomically and associatively related. In a follow-up study, Arias-Trejo and Plunkett (2013) found semantic priming effects in 24-month-olds for word pairs that were purely taxonomically related (e.g., *pig–dog*) or purely associatively related (e.g., *bone–dog*), suggesting that taxonomic and associative links between words contribute to structure-building processes in the emerging lexicon.

Theoretical analyses of the structure of typical 16- to 30-month-olds' vocabularies (Hills et al., 2009a, 2009b; Hills et al., 2010), derived from Communicative Development Inventories (CDI) data (Fenson et al., 1994) and adult feature norms (McRae et al., 2005), suggest that from as early as 20 months, these vocabularies possess structural properties characteristic of adult semantic networks. They predict a preferential acquisition of new words on the basis of frequency, co-occurrence, and phonological neighborhoods in the learning environment, suggesting that both taxonomic and associative links are driving lexical growth. These graph-theoretic analyses of infant and toddler CDIs offer convergent evidence that taxonomic and associative relationships between words play a causal role in the construction of the early lexicon.

Experimental evidence that word-to-word semantic links play a structuring role at an even earlier period in the development of the mental lexicon comes from a series of experiments using the all-auditory head-turn procedure. In these experiments, semantically related and unrelated lists of words are played to the infant listener (18-month-olds: Delle Luche et al., 2014, 24-month-olds: Willits et al., 2013). The logic behind these experiments assumes that infants compute the meanings of words when they hear them and are sensitive to any meaning relationship that the words may share. In Delle Luche et al. (2014), the related lists consisted of familiar names of objects from a single taxonomic category, such as body parts or food items. Consecutive words in these lists were not associated with one another, according to standardized adult association norms (Nelson et al., 2004). Unrelated lists consisted of familiar words taken from two categories but interleaved within the same lists (such as animals and clothes), again with no associated relationship between consecutive members of the list. Delle Luche et al. (2014) showed that 18-month-old infants listen longer to related lists than to unrelated lists. Since every effort was made to balance word frequency, syllabic length, and phonological overlap across the different lists, the authors concluded that these 18-month-old infants must be responding to the semantic relationships (or lack thereof) between the words within a list. These relationships were selected to be taxonomic in character and, therefore, the results of this experiment indicate that even 18-month-old infants have the capacity to construct lexical-semantic networks using taxonomic links.

Note that the experimental task used by Delle Luche et al. (2014) is quite different to classic word recognition experiments using intermodal preferential looking (IPL), where infants are presented with an auditory target word together with two images presented side by side (e.g., Bailey & Plunkett, 2002; Swingley et al., 1999; White & Morgan, 2008). Using IPL, it has been demonstrated that 18-month-olds (Arias-Trejo & Plunkett, 2010) and even 6-month-olds (Bergelson & Aslin, 2017) are slower to identify the image corresponding to a target word (e.g., *foot*) if the two images are perceptually and categorically related (e.g., *foot* and *hand*) than if the images are unrelated (e.g., *foot* and *milk*). It is important to emphasize that these findings do not indicate that infants have started to build a semantic network between spoken words, but rather that they have an early understanding of the perceptual and/or conceptual relationships between the objects depicted in the images. Indeed, as proposed by Arias-Trejo and Plunkett (2010), infants might have difficulties disambiguating two semantically related images (a foot and a hand) upon hearing a target word (*foot*), not because the word *foot* activates its semantic competitor *hand*—which could be taken as evidence of an early lexical-semantic network—but rather because common category membership can emphasize the perceptual similarities between the two images (Mandler & Bauer, 1988). Indeed, Arias-Trejo and Plunkett (2010) show that perceptual similarity plays a prominent role in undermining referent identification in an IPL task with both infants and adults. In Delle Luche et al. (2014) and in the study described below, the use of a head-turn preference procedure based exclusively on the presentation of spoken words, in the absence of any visual referents, suggests that any facilitative or inhibitory effects between words are due to activation occurring within a lexical-semantic network, and not simply within a general conceptual (or perceptual) system.

Further compelling evidence that infants and toddlers are sensitive to the semantic relations between words is provided in EEG studies of semantic priming effects. Torkildsen et al. (2007) presented pairs of words drawn from the same or different superordinate category (e.g., dog–horse vs. car–apple) to 24-month-olds while event-related potentials (ERPs) were recorded. Words taken from the same superordinate category produced a smaller and delayed N400 effect compared to words from different superordinate categories, suggesting that words from the same superordinate category were taken as more closely related. Torkildsen et al.'s results indicate the presence of priming effects for semantically related word pairs as early as 24 months of age, and point to the existence of a semantically structured lexical memory in late infancy. However, it is not possible to conclude from this study that the underlying semantic structures are organized according to taxonomic principles since the authors did not control for the frequency of co-occurrence of the taxonomically related words. In contrast, Rämä et al. (2013) recorded ERPs in 18- and 24-month-olds for pairs of words that were only taxonomically related (e.g., train–bike) or unrelated (e.g., chicken–bike). Importantly, the taxonomically related word pairs were associatively unrelated. The results also revealed an N400 priming effect in 24-month-olds and in 18-month-olds with higher vocabularies. The authors conclude that words are organized in the mental lexicon according to taxonomic principles at least as early as 24 months of age and even earlier for 18-month-old infants with a high vocabulary.

Sirri and Rämä (2015) conducted a similar experiment to that of Rämä et al. (2013) but with 18-month-old infants and varied the stimulus onset asynchronies between prime and target words. Using SOAs of 1000 and 1600 ms with word pairs that were either taxonomically related or unrelated, they found that the amplitudes of the N2 and N400 components were more negative for unrelated than taxonomically related word pairs, indicating taxonomic priming effects for the related word pairs and supporting the findings of Delle Luche et al. (2014) and Rämä, et al. (2013). Interestingly, Sirri and Rämä (2015) report that the amplitudes and distribution of the N2 and N400 varied with the SOA condition, leading the authors to suggest that automatic taxonomic priming effects occurred at an SOA of 1000 ms and that controlled priming effects might underlie the processes observed with an SOA of 1600 ms. Again, these authors concluded that taxonomic links between words are established by 18 months of age. It is also worth pointing out that the longer SOA (1600 ms) as used in the Sirri and Rämä (2015) study involves an Inter Stimulus Interval (ISI) of ~900 ms at which pure taxonomic priming effects are reported to be weak or absent in previous adult studies (McNamara, 2005; Murphy & Hunt, 2013; Seidenberg et al., 1984).

The body of evidence reviewed above points to a constructive role for taxonomic links between words in the infant lexical-semantic system as early as 18 months of age (Delle Luche et al., 2014; Rämä et al., 2013; Sirri & Rämä, 2015) and for associative/thematic links at least as early as 24 months of age (Arias-Trejo & Plunkett, 2009, 2013; Hills et al., 2010; Styles & Plunkett, 2009; Torkildsen et al., 2007). Previous research with adults and children also indicates that taxonomic and associative/thematic links play a prominent role in the structure of the mental lexicon, with some research with children suggesting that taxonomic links may be delayed compared to associative/thematic links (Unger et al., 2020). Furthermore, research with adults indicates that words that are *both* taxonomically *and* associatively/thematically related produce the strongest priming effects—the *associative boost effect*, with links that involve associative/thematic relations having longer-lasting priming effects than pure taxonomic relations (e.g., Moss et al., 1995; Shelton & Martin, 1992). This body of evidence leads us to predict that words that are both taxonomically and associatively related should prime each other in the 18-month-old lexicon, and that words which are both taxonomically and associatively related should produce stronger and longer-lasting priming effects than words that are only taxonomically related in the 18-month-old lexicon.

To evaluate these predictions, we used the same head-turn preference procedure (HPP) and stimuli as Delle Luche et al. (2014) to examine 18-month-olds' preferences for lists of related versus unrelated words. In Experiment 1, we explore the strength and duration of taxonomic priming effects between the words used by Delle Luche et al., by manipulating the interstimulus interval between the words in the lists. In Experiment 2, we introduce an associative boost by emphasizing the associative relations between words by reordering the words used by Delle Luche et al. to maximize the associative strength between consecutive words.

1.1 | Overview of experiments

The effect of ISI in adult priming studies is well documented: associative priming operates over longer intervals than taxonomic priming (e.g., Alario et al., 2000). In a previous experiment with 18-month-olds (Delle Luche et al., 2014), the ISI between words was 400 ms, a sufficiently short duration for taxonomically related words to prime each other: infants listened longer to related lists than unrelated lists. In order to track the relative dynamics of associative and taxonomic links between words at 18 months, we manipulated the ISI between spoken words in two experiments. Experiment 1 is similar to Delle Luche et al. (2014) except that the ISI was increased to 800 ms.[1] We predicted that increasing the ISI for these purely taxonomic lists would obliterate priming for these young participants. In Experiment 2, we introduced a boost to the priming effect by reordering the related word lists so that consecutive words were both taxonomically *and* associatively related. Given that associative priming is longer-lasting than pure taxonomic priming in adults (Alario et al., 2000), we expected the priming effect to reemerge.

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[1] Note that the contrast between ISIs used in Delle Luche et al. (2014) and Experiment 1 (400 vs. 800 ms) is very similar to the contrast between SOAs used by Sirri and Rämä (2015). The SOAs in Sirri and Rämä (2015) included the length of the prime word itself, whereas the ISIs used here and in Delle Luche et al. (2014) refer only to the interval *between* prime and target.

2 | METHOD

2.1 | Participants

Infants were healthy full-term 18-month-olds recruited from a pool of volunteer families on the Plymouth Babylab database. As in Delle Luche et al. (2014), only children who understood at least 50% of words in each category (animals, food and drinks, clothes, body parts) were included, based on parental completion of the Oxford CDI (Hamilton et al., 2000). A total of 48 children were successfully tested, 24 in each experiment (including 14 girls in Experiment 1 and 15 in Experiment 2). Their mean age was 17.86 months (Experiment 1: 17.85, range 17.26–18.85; Experiment 2: mean age 17.92 months; range 17.43–18.66). An additional 50 children were excluded for the following reasons: no completion of the 12 trials due to fussiness (*N* = 33; 9 in Experiment 1 and 24 in Experiment 2), experimental error or technical problem (*N* = 8; 5 in Experiment 1 and 3 in Experiment 2), at least 3 inattentions or two consecutive inattentions (*N* = 8; all in Experiment 2), and outlier (difference score below or above 2 standard deviations from the group mean, *N* = 1 in Experiment 2).[2] Communicative Development Inventories scores (see Table 5) were comparable across experiments in comprehension and production (all two-by-two comparisons were nonsignificant).

For comparability across experiments (including Delle Luche et al., 2014), we used a constant number of babies reaching data inclusion criteria, adopting the traditional sample size of 24 associated with experiments using this paradigm (Jusczyk & Aslin, 1995; Saffran et al., 1996).

The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Ethics committee in the Faculty of Science and Technology at the University of Plymouth.

2.2 | Materials

Stimuli were identical to those in Delle Luche et al. (2014). Four categories of objects were selected (food and drinks, clothes, animals, body parts; see Table 1) and 8 words per category were chosen using the Oxford CDI (Hamilton et al., 2000), so that on average they were known by 75% of 18-month-olds and by a minimum of 50% of children in the Oxford CDI norming data. In the current sample of 48 18-month-olds, animal names were known on average by 89.6% of children, clothes names by 86.2%, body parts by 87.8%, and food and drink items by 84.6%.

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[2] More children were excluded for fussiness and inattention in Experiment 2 than in Experiment 1. The two experiments were run a year apart, with a different team of experimenters. Although they were trained by the same staff and with the same protocol, and although the Head-Turn paradigm is immune to experimenter bias by design (as the experimenter is blind to which condition she/he is coding), it is sensitive to human factors. Indeed, it requires a unique set of skills to maintain a dynamic presentation of stimuli while monitoring and anticipating the child's attention level. Post hoc analyses showed first that in each experiment, children excluded for fussiness or inattention tended to score lower on CDI scores, at least in comprehension. Second, the likelihood of excluding children who started with a Related block versus an Unrelated block was equal in each experiment, discounting the possibility of an experimenter bias in selecting children based on the condition they were tested in. Finally, analyses of mean looking times for these children showed nonsignificant differences between Related and Unrelated conditions, in each experiment. For all these reasons, the only remaining explanation for the higher rejection rate in Experiment 2 than in Experiment 2 relates to human variability in administering the task. It is not uncommon to report a high attrition rate in studies using HPP with toddlers (see Hohle et al., 2006; Santelmann & Jusczyk, 1998), with discrepancies arising between experiments in the same lab. The only plausible explanation, as in our case, is probably due to human factors in administering the task and making decisions.

TABLE 1 List of stimuli used in experiments 1 and 2, organized in taxonomic categories

Animals	Clothes	Food & drinks	Body parts
Dog	Shoe	Biscuit	Nose
Cat	Nappy	Milk	Tummy
Cow	Sock	Apple	Ear
Pig	Hat	Bread	Finger
Horse	Coat	Juice	Mouth
Sheep	Bib	Toast	Tooth
Frog	Trousers	Cheese	Toe
Mouse	Boots	Cake	Arm

As in Delle Luche et al. (2014), the degree of association between words within or across categories was estimated using the University of South Florida adult free association norms (Nelson et al., 2004). The nature of the semantic link between words in related lists was most often purely taxonomic (e.g., *horse/mouse*), but for some there was a mix of taxonomic and associative relations (e.g., *cat/mouse*), a confound which was impossible to avoid entirely owing to the constraint of having to select words from a limited lexicon. However, lists were constructed in such a way that two words with a potential associative link as measured by the South Florida (SF) norms (e.g., *mouse/cat* or *mouse/cheese*) never occurred consecutively. To evaluate further the associative strengths between spoken words, we complemented the adult SF norms (Nelson et al., 2004) with computations from child-caretaker interactions corpora from CHILDES (MacWhinney, 2000). The following datasets were used from the Eng-UK CHILDES corpora (available at http://childes.talkbank.org/access/Eng-UK/): Forrester, Howe, Manchester, Wells, Lara, and Cruttenden. This used only speech from mothers and fathers to children aged between 1; 0 and 2; 0 (excluding 2; 0), providing a corpus of 141,493 words. All occurrences of words known by at least 50% of 18-month-olds in the Oxford CDI database were computed. Co-occurrences with any other target word within a 15-word window were extracted, excluding all function words, and any repetition of the target words within the window. For each particular word pair, for example, *cat* and *pig*, the probability of co-occurrence was obtained through the number of co-occurrences of *cat* followed by *pig* divided by the total number of occurrences of *cat*. It is worth noting that this method of calculating the probability of word co-occurrences is akin to the methods used in earlier models of word meaning such as Latent Semantic Analysis (Landauer & Dumais, 1997) and Hyperspace Analoge to Language (Lund & Burgess, 1996), which highlight both taxonomic and associative/thematic relations between words.

For the associations computed from the CHILDES corpora, an average of 6.8% of word-to-word transitions in the Related lists in Experiment 1 were associatively related (e.g., *dog* followed by *pig*, an association not found in the SF norms) with a mean association strength of 0.044 (e.g., the probability that *dog* would be followed by *pig*). For the Unrelated lists, no consecutive words were associatively related according to the SF norms, and only 1.2% of word-to-word transitions were related (e.g., *frog* and *shoe*) according to CHILDES computations, with a mean association strength of 0.05.

In Experiment 2, the stimuli were identical to those presented in Experiment 1, but this time, all pairings of associatively related stimuli were maximized in the Related condition. The 8 words in the Related lists were rearranged in pseudo-randomized lists so that on average 43.2% of word-to-word transitions were associative according to the SF norms (e.g., *cat/mouse*, or *sock/shoe*), with an average associative strength of 0.14. With associations computed from CHILDES, 19.8% of word-to-word transitions were related, with an average associative strength of 0.095. Unrelated lists were identical to those in Experiment 1.

Word lists were equated as much as possible in terms of phonological properties (number of syllables and phonemes per word, nature of the initial phoneme, complexity of syllabic structure), as illustrated in Table 2.

Words were recorded in an enthusiastic manner by a South-West of England native female speaker and normalized for amplitude using Praat (Boersma, 2006). Their mean duration was 700.2 ms (SD 109.6 ms), with no difference across the four categories (F (3, 29) < 1). Pseudo-randomized lists were created for each category or mixture of categories. Within each list, the 8 words were concatenated with an ISI of 800 ms and the resulting lists were repeated 3 times to create sound files averaging 35 s for both the Related and the Unrelated conditions.

In a within-participant design, each child heard a block of 6 Related lists (from two categories) and a block of 6 Unrelated lists (mixing the remaining two categories), with the order of blocks counterbalanced across children. Table 3 shows an example of lists heard by one particular child in Experiment 1 who started with the Related condition (animals and food and drinks) followed by the Unrelated condition (body parts and clothes interleaved). Across all children, each category would

TABLE 2 Phonological properties of stimuli used in each experiment

	Mono	Di/tri	Phon	V-ini	Pl-ini	Fr-ini	N-ini	Syll struct
Food & drinks	6	2	4	1	4	0	1	7
Animals	8	0	3.37	0	4	3	1	5
Clothes	6	2	3.75	0	4	3	1	6
Body parts	6	2	3.75	2	3	1	2	7

Note: [Column legends: Mono and Di/tri refers to the count of monosyllabic words and di- or trisyllabic words, respectively. Phon: mean number of phonemes per word. V-ini: number of words with a vowel as initial phoneme. Pl-ini, Fr-ini and N-ini: number of words starting with a plosive, a fricative or a nasal consonant. Syll struct: number of different syllabic structures].

TABLE 3 Example of list of words presented to infants in the Related condition (top) and Unrelated condition (bottom) in Experiment 1

Related Lists					
Dog	Biscuit	Cat	Apple	Sheep	Juice
Pig	Milk	Cow	Milk	Frog	Cake
Cat	Apple	Sheep	Toast	Cow	Cheese
Sheep	Cheese	Pig	Juice	Dog	Toast
Horse	Juice	Dog	Bread	Mouse	Milk
Mouse	Bread	Frog	Cake	Pig	Biscuit
…	…	…	…	…	…

Unrelated Lists					
Shoe	Coat	Bib	Nose	Tooth	Finger
Trousers	Shoe	Finger	Trousers	Nose	Tooth
Nose	Finger	Coat	Arm	Coat	Bib
Arm	Trousers	Nose	Coat	Shoe	Shoe
Coat	Arm	Trousers	Tooth	Finger	Nose
Bib	Nose	Tooth	Bib	Arm	Trousers
…	…	…	…	...	...

Note: Each column represents a list of words. This example uses animal names (black) and food and drink items (orange) in the Related lists, and clothes (black) and body parts (orange) in the Unrelated lists. This is adapted from Delle Luche et al. (2014).

appear as often in the Related and the Unrelated condition, with each pairing of categories equally represented. Table 4 shows an example of lists heard by one child in Experiment 2, where words in the Related condition were reorganized to maximize the associative links between consecutive words.

2.3 | Procedure

Ethical approval was obtained from the University of Plymouth Faculty of Health and Human Sciences Research Ethics Committee. After informed consent was obtained from the parent, the child sat on the parent's lap in the experimental head-turn booth. The parent wore headphones playing loud music to mask the auditory stimuli. The experimenter sat outside but could observe the infant via a video camera (without sound capture). At the beginning of each trial, a green light flashed directly in front of the infant to get her attention (distance from chair to central light: 112 cm). When the experimenter judged that the infant was looking at the central light, she/he started the trial, causing the green light to stop and a red light to start flashing either to the left or the right side (randomized and counterbalanced) of the infant (distance between the two lights: 122 cm). When the infant turned toward the side where the light was flashing, as assessed by the experimenter, a sound file was played via a speaker located just below the flashing light, until the end of the file, or until the child looked away for more than 2 s. Any trial during which the infant looked away within 1.5 s was aborted and the word list was repeated. If two consecutive trials were aborted, or if three trials were aborted during the experiment, the participant's data were excluded for inattentiveness. Between trials, the experimenter triggered the central fixation green light when she/he judged the child to be ready, and when the child was fixating

TABLE 4 Example of list of words presented to infants in the Related condition (top) and Unrelated condition (bottom) in Experiment 2

Related Lists					
Dog	Biscuit	Cat	Apple	Sheep	Juice
Cat	Milk	Sheep	Bread	Frog	Milk
Sheep	Juice	Cow	Toast	Cow	Cheese
Pig	Cake	Horse	Juice	Dog	Cake
Horse	Cheese	Dog	Biscuit	Pig	Biscuit
Mouse	Bread	Frog	Milk	Horse	Apple
…	…	…	…	…	…

Unrelated Lists					
Shoe	Coat	Bib	Nose	Tooth	Finger
Trousers	Shoe	Finger	Trousers	Nose	Tooth
Nose	Finger	Coat	Arm	Coat	Bib
Arm	Trousers	Nose	Coat	Shoe	Shoe
Coat	Arm	Trousers	Tooth	Finger	Nose
Bib	Nose	Tooth	Bib	Arm	Trousers
…	…	…	…	...	...

Note: Each column represents a list of words. This example uses animal names (black) and food and drink items (orange) in the Related lists, and clothes (black) and body parts (orange) in the Unrelated lists. Unrelated lists are identical to those used in Experiment 1, whereas words in the Related lists are rearranged to maximize associative links across consecutive items. Words highlighted in yellow are associatively related to the immediately following word, as indicated by South Florida norms and/or CHILDES analyses.

the green light, she/he would trigger the next trial. Typically, between 3 and 10 s would elapse between the end of a trial and the start of another.

After two training trials during which the children heard a piece of music (to ensure they understood that sounds could emanate from the left or the right when they looked toward the corresponding light), each child was presented with a first block of 6 lists and, following a half-minute break, with a second block of 6 new lists. In a within-participant design, children were tested in two conditions: Related and Unrelated. For example, as illustrated in Table 3, a child tested in the Related condition first would hear a block composed of words from the animal and food and drink items, so that 3 lists would be made of animal names only, and 3 lists would be made of food and drink names only. After a short break, 6 lists of words from the two other categories mixed together (in Table 3, clothes and body parts) would follow. Any looking time shorter than 1.5 s on one list, an inattention, would automatically result in the termination of that list and the list being repeated immediately (with the original looking times discarded). Any look away from the light for more than 2 s would result in the termination of the list and the recentering of attention on the central light. The side of list presentation (left or right) was randomized across children and lists.

3 | RESULTS

For each child in each experiment, mean looking times toward each type of list (Related or Unrelated) were calculated, after discarding looking times shorter than 2 s to ensure sufficient time to hear a minimum of 2 consecutive words, as in Delle Luche et al. (2014). Infants completed a similar number of lists in each condition and across both experiments (see Table 5).

Looking times were normally distributed in each condition and in each experiment, as verified by a Shapiro-Wilk test. An ANOVA with Order (Related block first/Unrelated block first) and Condition (Related/Unrelated) was conducted on mean looking times; since Order did not have any effect nor interacted with condition, it was removed from further analyses. Therefore, subsequent paired sample t-tests were used to compare looking times in Related and Unrelated conditions, with results illustrated in Figure 2.

In Experiment 1 (Figure 2, Experiment 1), no systematic difference was found between mean looking times in the related ($M = 14.70$, $SD = 5.25$) and unrelated lists ($M = 13.68$, $SD = 4.44$) at 800 ms, indicating a lack of taxonomic priming, t (23) = 1.61, ns, 95% confidence interval (CI) = [−0.29, 2.33], even though such an effect was observed with an ISI of 400 ms (Delle Luche et al., 2014: see Figure 2, Experiment Zero). In Experiment 2 (Figure 2, Experiment 2), longer looking times were found for related lists ($M = 13.37$, $SD = 5.0$) as compared to unrelated lists ($M = 11.44$, $SD = 4.24$), t

TABLE 5 Summary of conditions and results for experiments 1 and 2. The corresponding numbers for Delle Luche et al. (2014) are tabulated as Experiment Zero for comparison. Children were 18 months old in all three experiments

Exp	Condition	ISI	CDI comp	CDI prod	NRel	NUnrel
0	Taxonomic	400	233.3 (73.5)	73.1 (68.2)	5.8	5.9
1	Taxonomic	800	210.9 (81.9)	63.6 (52.9)	5.8	5.9
2	Taxo/Assoc	800	241.8 (82.8)	73.1 (72.0)	5.7	5.7

Note: [Condition: type of relation being tested in the Related condition (taxonomic +/-associative). ISI: Inter-Stimulus-Interval in ms. CDI Comp and CDI Prod: mean number of words understood or produced, respectively, in the Oxford CDI, out of 416 (SD in bracket). NRel and NUnrel: mean number of completed lists per child in the Related and Unrelated condition, respectively].

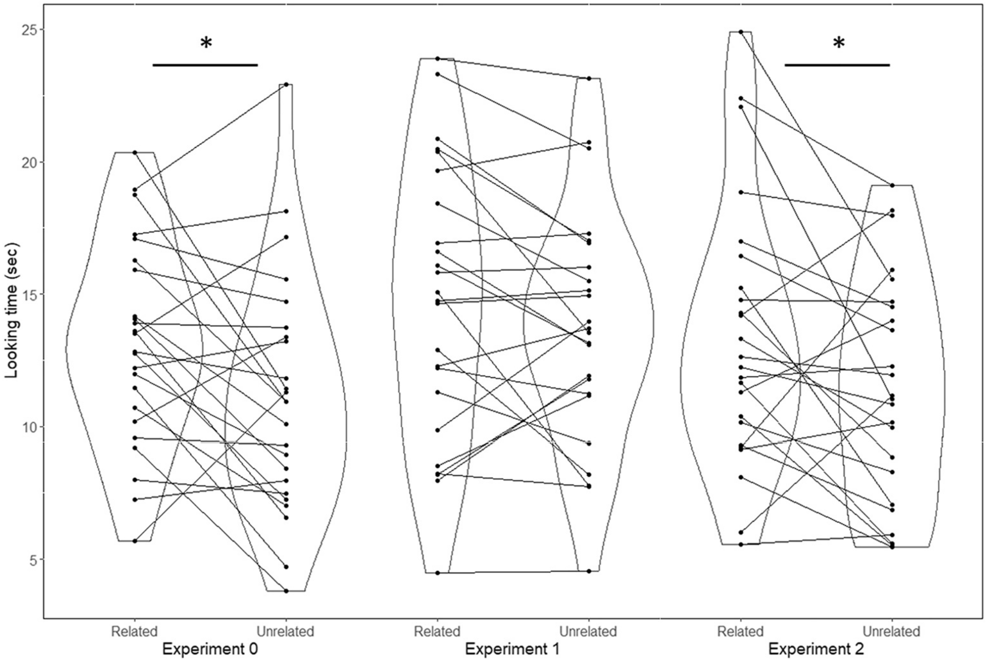

FIGURE 2 Results of Experiment 1 (800 ms ISI) and Experiment two (800 ms ISI) with results from Delle Luche et al. (2014) replotted as Experiment Zero (400 ms ISI). For each experiment, violin plots indicate the looking time distributions for the Related and Unrelated conditions. Significant differences ($p < 0.05$) between conditions are indicated as asterisks in each Experiment

(23) = 2.20, $p = 0.038$, CI = [0.12, 3.76], Cohen's $d = 0.41$, indicating priming for taxonomically and associatively related words.

Although each experiment was designed to test a particular hypothesis and therefore required separate analyses as displayed above, we ran an ANOVA with all three experiments (including Experiment Zero) to compare looking times in the related and unrelated conditions. There was a main effect of lists (longer listening times for related over unrelated lists; F (1, 69) = 13.43, $p < 0.001$, $\eta^2 = 0.16$) but no interaction between lists and experiments (F (2, 69) < 1). When only Experiments 1 and 2 are considered, again a main effect of lists was found (F (1, 46) = 7.43, $p = 0.01$, $\eta^2 = 0.14$) and no interaction between lists and experiment (F (1, 46) < 1). We note that similar effect sizes have been reported using a similar task with older infants (Willits et al., 2013).[3]

4 | DISCUSSION

The two experiments reported in this paper investigated the efficacy of taxonomic and associative links between words to produce priming effects in 18-month-olds. Using the original findings reported by Delle Luche et al. (2014) as a starting point, where taxonomic priming was obtained with an ISI of 400 ms between words, we extended the ISI to 800 ms and manipulated the relationship between consecutive

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[3] In Experiment 1, infants who understood and produced more words according to their Oxford CDI scores (see Table 5) listened longer to Unrelated lists as compared to those who knew or produced fewer words (comprehension: Spearman $r = 0.48$, $p = 0.019$; production: $r = 0.53$, $p = 0.01$). No other correlation between Oxford CDI scores and looking times was significant, including Experiment 2.

words: purely taxonomic in Experiment 1, and taxonomic and associative in Experiment 2. No evidence of priming was found in Experiment 1, suggesting that taxonomic priming decays somewhere between 400 ms (Delle Luche et al., 2014) and 800 ms (Experiment 1). In contrast, when we introduced an associative boost to the priming effect by reordering the related word lists so that consecutive words were both taxonomically *and* associatively related, we found evidence of priming (Experiment 2). This established, in line with adult studies (e.g., Alario et al., 2000), the existence of an associative boost at 18 months and that the associative priming boost is longer-lasting than pure taxonomic priming at 18 months.

These findings, together with other infant studies reviewed in the Introduction, demonstrate that by 18 months, infants have begun to construct a lexical-semantic network based on taxonomic and associative relationships between spoken words; they listen longer to lists of words that are taxonomically related to each other or taxonomically and associatively related to each other, as compared to unrelated word lists. Longer looking indicates that words in related lists prime each other through a network of links based on taxonomic and associative relationships as early as 18 months of age. If the ISI between words in related lists is increased to 800 ms, the priming effect disappears for the purely taxonomic lists but remains intact for lists that contain consecutive words that are both taxonomically and associatively related. These results suggest that associative links between words can act in tandem with taxonomic links to produce an associative priming boost and that the combined action of associative and taxonomic relations produces longer-lasting priming effects in 18-month-olds.

Similar patterns of priming for associative and taxonomic links between words are well-established in the adult literature. In particular, an associative priming boost is observed for words that are both taxonomically and associatively related, and facilitative priming effects are longer-lasting (~800 ms) for associatively related words as compared to taxonomically related word pairs (see Alario et al., 2000; Lucas, 2000; McNamara, 2005, for extensive summaries). This convergence with findings from the adult literature points to the possibility that some basic structural and processing components observed in the adult lexical-semantic system are already in place for 18-month-old infants.

Additional sources of convergent evidence regarding basic structural components of the infant lexical-semantic system were reviewed in the Introduction; ERP investigations have established the existence of taxonomic priming in 18-month-olds (Rämä et al., 2013; Sirri & Rämä, 2015) and taxonomic/associative/thematic links at least as early as 24 months of age (Torkildsen, et al., 2007). Behavioral studies also point to the presence of taxonomic and associative priming at least as early as 24 months of age (Arias-Trejo & Plunkett, 2013; Styles & Plunkett, 2009) or even earlier (Arias-Trejo & Plunkett, 2009; Delle Luche et al., 2014). Computational analyses of infant and toddler communicative development inventories (CDIs) show that both taxonomic and associative relationships between words are predictive of vocabulary growth during the second and third years (Hills et al., 2009a, 2009b, 2010). The current results provide further experimental support for the view that semantic networks are under construction at an even earlier stage of lexical-semantic development than current computational CDI analyses have envisioned.

Distributed network models of adult semantic priming also postulate a distinction between taxonomic and associative priming, in which facilitative priming is short-lived in the former but longer-lasting in the latter (e.g., Plaut & Booth, 2000). Under these kinds of models, taxonomic priming is explained in terms of semantic feature overlap between prime and target items, whereas associative priming occurs as a result of the frequent co-occurrence of words during learning. The relatively short-lived duration of facilitative taxonomic priming is thought to derive from the inhibiting effects of nonoverlapping semantic features between prime and target (see Introduction). The priming effects and their relative durations reported in the current study with infants are consistent with these theoretical accounts of adult semantic priming. Infants use perceptual and functional features of objects to build taxonomic categories of objects well before 18 months of age (Mandler & Bauer, 1988;

Mareschal & Quinn, 2001). Such an ability has the potential to underpin the capacity to compute featural overlap across semantic representations. Infants are also sensitive to the co-occurrence statistics between sequences of syllables well before their first birthday (e.g., Saffran et al., 1996), an ability that has the potential to support the formation of associative links in the emerging lexicon.

Plaut and Booth (2000) argued that associative and taxonomic priming effects are subject to individual variation and developmental differences, and they illustrated this variability in a series of experiments with 8- to 11-year-old children and adults, with accompanying simulations using distributed network models. Factors that played an important role in their experiments and simulations were word frequency and the robustness/strength of semantic representations. We envision that similar factors may be at work in the 18-month-olds participating in the current experiments. Semantic development in 18-month-olds is by no means complete, and exposure to word-word co-occurrences will vary greatly across infants, leading to variable patterns of taxonomic and associative priming, respectively. It is also possible that the asymmetries in the duration of facilitative priming effects for taxonomically versus associatively related words found in adults and our current population of infants may not be uniform across items or development.

If Plaut and Booth (2000) are correct in their claim that facilitative taxonomic priming is a consequence of semantic feature overlap, then weak semantic representations should lead to a reduction in the strength of the priming effect. Weak semantic representations should lead to an expansion of the time course over which taxonomic priming operates due to the weaker inhibitory effects of nonoverlapping semantic features, though the magnitude of the priming effect will be reduced. Of course, associative priming will also be affected by the frequency of word-word co-occurrences, but experience of these co-occurrences seems more likely to impact the strength of associative priming rather than its duration. Insofar as the asymmetry in the duration of taxonomic and associative priming is a signature of adult-like taxonomic and associative connectivity, the results of our 18-month-old infants point to their possession of an adult-like lexical-semantic system. The structure of this network exploits taxonomic and associative relationships between words, and the processes by which activity propagates through the network point to the existence of a distributed semantic system by 18 months of age.

This conclusion converges with that of Sirri and Rämä (2015) who reported ERP signatures indexing taxonomic priming effects in 18-month-olds. It is noteworthy that ISI also influenced the patterns of priming in their study, such that at short ISIs taxonomic priming effects were indexed by N2 and N400 signatures, whereas at longer ISIs the N2 component was modulated at frontal sites. The authors attributed these differences to the emergence of *controlled* as opposed to automatic priming effects at longer ISIs. In the current study, we have attributed the emergence of the priming effects at the longer ISI to the *associative boost*. Since none of the stimuli were associatively related in the Sirri and Rämä (2015) study, it is unlikely that the ISI differences they observed are attributable to associative links. However, we note that we did not observe any evidence for taxonomic priming in the taxonomically related word lists at the long ISI in our study (Experiment 1). Whether this difference between our results and that of Sirri and Rämä (2015) is due to the different methods used, involving perhaps a greater sensitivity of EEG measures over eye-tracking measures, is unclear. It is possible that the introduction of associative relations between words in our study also triggered a more *controlled* form of priming. Indeed, a more controlled form of priming may be the source of the associative boost observed in our study. Nevertheless, this does not explain why controlled priming was not observed at long ISIs for the lists in our study that were only taxonomically related (Experiment 1), given that Sirri and Rämä (2015) did observe this. We suggest that a more parsimonious explanation of our findings, convergent with previously reported adult studies, is that the infants in our study were sensitive to an associative boost introduced by the reordering of the word lists in Experiment 2.

It is instructive to consider whether the different patterns of listening in Experiments 1 and 2 were simply due to highlighting the associative relationship between words in the latter as compared to the former. In other words, longer looking in Experiment 2 as compared to Experiment 1 may not be the result of an *associative boost* of the taxonomic relationships between the words but just the associative relationships themselves. One way to test this hypothesis would be to run a third experiment in which there are no taxonomic relationships between the words but only associative relationships. If associative relationships are entirely responsible for longer looking, we would predict a similar pattern of looking in this hypothetical third experiment as that observed in Experiment 2. This outcome would also be consistent with the well-established finding in adults that associative priming is longer-lasting than taxonomic priming. A fuller investigation of the nature of the associative boost reported in this paper should therefore systematically manipulate the strength of the taxonomic and associative relationships between words. Although this is an ambitious undertaking with 18-month-old infants, such an investigation would permit the determination of the relative impact of taxonomic and associative relationships on looking times at different ISIs, and provide important clues to the ontology of taxonomic and associative relationships in the infant lexical-semantic system. The current study constitutes a first step in that program of research.

An important limitation of the current study is that participants were not randomly assigned to Experiments 1 and 2. In particular, for logistical reasons, Experiment 2 was carried out a year after Experiment 1. Therefore, the manipulation between the two experiments was confounded by the population of infants from which the participants were drawn, as well as the different team of experimenters who performed the experiments, with the different attrition rates across the two experiments reported above likely resulting from human factors. Ideally, both experiments would have been conducted concurrently with random assignment to each experiment. Replication of these findings should include this additional control of random assignment.

Taxonomic and thematic priming are considered to recruit distinct neural pathways in adults. In particular, taxonomic relations between words predict activity in the anterior temporal lobe, whereas both kinds of relations implicate the temporoparietal junction (e.g., Lewis et al., 2015). Given the close correspondence between associative and thematic relationships, we might reasonably suppose a similar dissociation between the neural pathways underpinning taxonomic and associative priming in adults. Distributed network models of semantic priming are agnostic as to the separation of neural pathways underlying different types of priming. Nor is it clear how these distinct neural pathways lead to differences in the durations of taxonomic and associative priming effects in adults. However, the separation of these processes in the adult brain raises fascinating questions as to how and when these separable neural systems become established in the infant brain. We have shown how these priming effects can be distinguished behaviorally during infancy. An important next step will be to identify the neural underpinnings of taxonomic and associative priming in the infant brain.

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CONFLICT OF INTEREST

There were no conflicts of interest for the authors in carrying out this research.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the last author upon reasonable request.

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