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How do infants build a semantic system?

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Abstract

Do infants learn their early words in semantic isolation? Or do they integrate new words into an inter-connected semantic system? In an infant-friendly adaptation of the adult lexical priming paradigm, infants at 18 and 24 months-of-age heard two words in quick succession. The noun-pairs were either related or unrelated. Following the onset of the target word, two pictures were presented, one of which depicted the target. Eye movements revealed that both age groups comprehended the target word. In addition, 24-month-olds demonstrated primed picture looking in three measures of comprehension: Named target pictures preceded by a related word pair took longer to disengage from and attracted more looking overall. The finding of enhanced target recognition demonstrates the emergence of semantic organisation by the end of the second year.

Keywords: lexical priming, semantic networks, vocabulary development, language acquisition, lexical comprehension, infancy

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Introduction

How and when do infants integrate the words they understand into an inter-connected semantic system? Between the ages of one and two, infants develop a prodigious word-learning ability (Bloom 2002; Fenson, et al. 1994; Hamilton, et al. 2000). Over the past three decades, cross-sectional and longitudinal information about the size of the lexicon, and types of words known to young word-learners has been collated using structured parental interviews, videotaped observation sessions, vocabulary checklists, and comprehension assessments (e.g., Benedict 1979; Bretherton, et al. 1983; Fenson, Dale, Reznick, Bates, Thal and Pethick 1994; Nelson, K. 1973). Experimental studies have also explored the processes involved in learning individual words (e.g., Halberda 2003; Markman 1989; Merriman and Bowman 1989; Schafer and Plunkett 1998). Yet little is known about how and when infants integrate their accumulating word-knowledge into a system of meaningful relationships. Do their lexicons encode relatedness? Or do they maximise difference? Is the infant lexicon a scaled-down version of the adult semantic memory system? Or is there discontinuity between the early stages of word learning and later semantic organisation? At present, there is little evidence about the precise nature of infant lexicon organisation, or about when young word learners begin to develop an adult-like semantic system encoding relationships such as association, functional information and taxonomic category organisation.

Many current models of adult language processing propose that the adult lexicon functions like a network

of nodes (words) linked by connections through which activation flows during linguistic processing (Anderson 1983; Collins and Loftus 1975). These 'spreading activation' models of semantic memory are supported by evidence from on-line language processing tasks. For adults, context has a strong effect on the ease and speed of linguistic processing, and on behavioural responses to language. Both visual and auditory context are known to influence the speed of lexical processing (Antos 1979; Meyer and Schvaneveldt 1971; Radeau 1983) and ambiguity resolution (Swinney 1979). The effect of prior context on performance in behavioural tasks is termed priming.

Spreading activation models account for the effects of priming as activation flowing from a prior stimulus (the prime) supplementing the incoming bottom-up activation from the test stimulus (the target) itself. When two words are presented in quick succession, recognition of the target word is faster (Meyer and Schvaneveldt 1971), and more accurate (Antos 1979) following a related word. The spreading activation model implies that word-word relationships are thus structurally encoded in the network architecture, as links between individual words. Priming has demonstrated various kinds of semantic relationship in the adult lexicon, including word association (Meyer and Schvaneveldt 1971), taxonomy (Moss, et al. 1995; Nation and Snowling 1999), shared semantic features (Moss, et al. 1997), and thematic relationships (Moss, Ostrin, Tyler and Marslen-Wilson 1995). This leads to a complex model of the adult lexicon, in which each word exhibits a variety of connections to other words. Despite

the complex organisation of the adult lexicon, little is known about its development.

Semantic islands or bridges

In the early stages of word learning, the young word learner might encode individual words in semantic isolation – with the representation of each word discrete, and maximally differentiated from the representations of others. A lexicon containing a small number of these ‘semantic islands’ would have the advantage of low confusability between known words. Early word learners might be expected to show less overgeneralisations between words they know than between items for which only one word has entered the lexicon. For example, an infant who understands both *cat* and *dog* might be less likely to overgeneralise the word *cat* to mean *dog*, than an infant who understands only *cat*.

However, as the lexicon grows, and increasing numbers of words are added, discrete representations for every item might become harder to achieve. Furthermore, just as trying to find a particular book in a random stack takes longer than finding the same book in a systematically organised library, an unsystematic semantic system would be predicted to reduce certain types of language processing efficiency – in particular, the kinds of processing advantages demonstrated in adult priming studies. While discrete representations may be advantageous in the early stages of lexicon development, they would ultimately prove to be unsustainable over development. If infant lexicons initially encode difference at the expense of relatedness, re-organisation would be required in order to reach the adult state.

Alternatively, if the semantic representations of early words encode semantic relatedness between words, the semantic system might be adult-like from its very earliest stages. In an interconnected lexicon, thinking about a cat, for example, would make it easier to access the word *dog*; ‘Bridges’ between the meanings of words facilitate easy movement between related ‘islands’. While benefiting from this kind of processing advantage, a lexicon which is interconnected from its earliest stages might be expected to exhibit *more* over-generalisation between known items, as interconnected representations would increase the likelihood of accessing the wrong word. Indeed, it may prove to be difficult to discriminate spreading activation between closely related words from over-generalisation of one word to another. However, the main advantage of this account of semantic development is that it suggests that there would be no discontinuity in the organisation of the semantic system over lexicon development.

Models of the lexicon under development

One model of lexical network development comes from the field of computational linguistics. Steyvers and Tenenbaum (2005) tested the mathematical properties of networks created from four natural-language data

sets: Two networks were created from the norms of the University of South Florida Free Association Norms (USFFA: Nelson, D. L., et al. 1998); one network was created from the synonymy listings of Roget’s Thesaurus (Roget 1991); and the fourth, was the digital database WordNet (Miller 1995). They found that all four data sets shared the statistical properties of a ‘small-world’, ‘scale-free’ network. Small-world networks are characterised by a power-law distribution of connectivity, with the majority of items sharing very few connections with others. This results in small-scale local clusters, connected by a few highly connected ‘hubs’. The scale-free properties of this architecture suggest that local organisation remains consistent throughout development, and is gradually scaled-up to include more small neighbourhoods and hubs as new nodes are added to the system.

In addition, Steyvers and Tenenbaum were able to model node-by-node network growth according to the power-law attachment pattern, by ensuring that highly connected words were more likely to attract connections from new words. Having demonstrated the mathematical fit of the preferential attachment mechanism, they tested one of its main predictions: that words acquired earlier in development would have a ‘head start’ in the number of incoming and outgoing connections, compared to later acquired words. Words in the three adult networks did show a strong relationship between connectivity and age-of-acquisition (AoA). That is, words learned earliest were those which were most deeply integrated into the semantic structure.

To clarify whether this mathematical model matched real-time acquisition data, a recent investigation tested whether the preferential attachment account matched longitudinal reports of the words entering 20 infant lexicons, over a 15-month period (16-months to 30-months). Hills, Maouene, Maouene, Sheya and Smith (2008) tracked network growth across basic-level nouns from the MacArthur-Bates Communicative Development Inventory for Toddlers (Fenson, Dale, Reznick, Bates, Thal and Pethick 1994), assessed at monthly intervals. Across the 130 nouns selected for comparison, a month-by-month model which connected newly acquired words according to known associates exhibited the preferential attachment pattern predicted by Steyvers and Tenenbaum (2005). A month-by-month network built according to perceptual features alone did not share these statistical properties. These models of lexical network development predict that early lexicons will be semantically structured, and that the organisation of the network may well be adult-like, and continuous throughout development.

However, given the possibility of structural re-organisation during development, it is impossible to know whether adult-like architecture begins at the very earliest stages of word learning and continues, unchanged, into adulthood; or whether large-scale re-organisation takes place in early development, with the

scale-free, small-world characteristics of the adult lexicon emerging gradually as the lexicon expands. What is needed is experimental evidence of whether semantic relationships are evident in the early lexicon. Lexical priming offers a possible platform for establishing behavioural evidence about relationships in the early lexicon.

Experimental evidence of lexicon organisation during childhood

Priming studies involving reading have demonstrated that adult-like lexical relationships between associates are evident in 7- to 9-year-olds (Schvaneveldt, et al. 1977). To date, few experimental studies have sought to confirm the early connectivity account in the language processing behaviour of younger children or toddlers. Traditional priming studies rely on adults' reaction times (RTs) during conscious decision-making tasks (such as lexical-decision, categorisation or semantic feature analysis), which are typically employed over large data sets. Barriers to the use of adult methodologies in early development have included participants' limited attention spans, relatively small vocabularies and lack of explicit metalinguistic knowledge (e.g., whether a string of sounds is a 'word').

A small number of auditory priming methodologies have been extended for use with school-aged children and toddlers, demonstrating a) that associative relationships prime lexical response times for 6- to 7-year olds (Radeau 1983); b) that taxonomic, thematic and associative relationships prime reaction time for normally developing school children at 10 years-of-age (Nation and Snowling 1999); c) that taxonomic, thematic and perceptual relationships prime reaction time in an object decision task for 6- to 8-year-olds (Hashimoto, et al. 2007); d) that thematic relationships prime the speed of picture naming at 6 years-of-age, along with taxonomic relationships at 8 years-of-age (McCauley, et al. 1976); and e) that associative relationships prime accuracy in verbal memory tasks for 3- to 4-year-olds (Krackow and Gordon 1998). Together, these studies suggest that lexical relationships are evident in lexicon structure by the pre-school years. However, the applicability of these methods to younger participants remains limited by task complexity.

In an alternative approach, researchers in the field of electrophysiology have sought to replicate adult patterns of brain activity in infant studies. The 'N400 component' in adult event-related potentials (ERPs), is understood to index semantic congruency (Kutas and Hillyard 1980), semantic relatedness (Federmeier and Kutas 1999) and category organisation (Heinze, et al. 1998). The ERP method can be used to observe passive language processing, without complex task demands. Recent developmental studies have suggested that infant analogues to the adult semantic component are evident during on-line language processing (Friedrich and Friederici 2004; 2005a; 2005b; Torkildsen, et al. 2007). However, as Torkildsen

and colleagues acknowledge, it is unclear what functional effect these ERP signatures might have on the ease or speed of linguistic processing, as these passive tasks did not assess how quickly or easily infants comprehended the words. Furthermore, the ERP method makes it difficult to take into account whether individual infants understood the particular words used in the test. Differences between the test conditions could have been influenced by individual differences in which words were known to each infant. Thus, although children two years and under show patterns of electrical activity which are similar to adult language processing effects, without corroborating behavioural evidence it is unclear whether similar brain signatures are markers of the same cognitive effect.

Introducing a new method: Primed IPL

It thus remains to be seen whether adult-like primed processing effects can be replicated in an on-line *behavioural* task for infants, in which item-level sensitivity is achievable. If infants' online language processing is affected by verbal context in sequential word presentation (as indexed, for example, by lexical comprehension), it would provide strong support for a model of lexicon development which features adult-like inter-connectivity from a very early age. The goal, therefore, is to develop an infant-friendly behavioural task in which stimulus presentation can be systematically varied to produce a priming task, and which uses ease and speed of lexical comprehension as an index of online language processing.

The intermodal preferential looking (IPL) task established by Golinkoff and colleagues (1987) is a free-looking task for infants, in which looking behaviour is monitored while a pair of images is presented, and auditory stimuli are introduced. When one of the images is labelled, infants' looking behaviour shows an increase in preference for the named image (Reznick 1990). The IPL task is a flexible framework which indexes lexical comprehension of individual items, and which is sufficiently sensitive to demonstrate infants' sensitivity to auditory manipulations (Fernald, et al. 2001; Mani and Plunkett 2007; Swingley and Aslin 2007; White and Morgan 2008), as well as to item typicality (Meints, et al. 1999). Contemporary implementations of IPL also employ offline frame-by-frame analysis of video recordings, thus introducing high temporal accuracy. The IPL method bears substantial methodological similarity to adult eye tracking methods such as the visual world paradigm (e.g., Huettig and Altmann 2005; Huettig and McQueen 2007; Kamide, et al. 2001), but by limiting the number of presentation areas, and using frame-by-frame visual inspection by a highly trained observer, the IPL method has the advantage of being able to tolerate substantial movement by the infant participant without the need for distracting apparatus (such as head restraint or a head mounted tracking system).

In this paper, we investigate the effect of lexical context on the looking behaviour of infants in their second year, using a primed IPL task. This new method replicates the sequential stimulus presentation of adult priming studies, but replaces the 'lexical decision task' with a period of free-looking to a picture pair. To create the priming context, two words are presented acoustically prior to the onset of the picture pair. The first word is the prime, and the second, the target, which names one of the pictures in the pair. Prime and target words are either related (e.g., *cat* and *dog*) or unrelated (e.g., *plate* and *dog*). This manipulation allows us to investigate the central question of whether infants' performance in a primed referent identification task shows evidence of a semantic system which is consistent with the early connectivity account.

Method

Participants were recruited from a database of parents who had previously expressed an interest in participating in developmental studies. In the week before visiting the laboratory, primary caregivers of all participants filled out the British CDI (Hamilton, Plunkett and Schafer 2000), an adaptation of the MacArthur CDI (Fenson, Dale, Reznick, Bates, Thal and Pethick 1994). The British CDI is a list of 416 words measuring both receptive and productive vocabulary. Parents brought their completed CDIs with them to the testing session. In a small number of cases, they completed the form on the day of testing, either during their visit, or returned by post shortly after. Infants who visited the laboratory were given a small gift for their participation.

Seventy two 18-month-olds were tested (40 males, 32 females; mean age: 18.2 months; range: 17.1 to 18.8). Seventy two 24-month-olds were tested (34 males, 38 females; mean age: 24.1 months; range: 23.4 to 25.0). Twenty five additional infants were removed and replaced, for failure to complete, fussiness, parental failure to return CDI forms, and for experimenter error. Total receptive CDI scores were checked against previously collated norms, and infants' comprehension of test items was assessed. Following preliminary analysis, three eighteen-month-olds were removed from analysis for extremely low receptive CDI scores (in the 5th percentile of previously collected CDIs

for 18-month-olds), and four further 18-month-olds were removed from analysis when it was observed that they contributed trials to only one priming condition.

Materials

In order to use the same stimuli across the two age groups, the younger age (18 months) was used as baseline in stimulus selection. Five hundred and forty eight previously collected British CDIs were consulted (Hamilton, Plunkett and Schafer 2000). Thirty six words were selected for use in the current study, all of which were 'understood' by more than 50% of 18-month-olds, according to the 179 CDIs that fell in the age range 17.5 to 18.5 months-of-age. Two stimulus lists were created in which twelve words acted as auditory 'primes' and twelve words acted as auditory 'targets,' referents of which were depicted on-screen. Referents of the twelve remaining words were used as unnamed 'distracters' which appeared alongside the target picture during the test phase of the trial. Two stimulus lists were created, and are given in the Appendix. Picture pairs were yoked across lists.

Between lists, each target occurred with two different primes, a 'related' prime in one list and an 'unrelated' prime in the other. Related word-pairs had an attested forward association in adult British English (Moss, Ostrin, Tyler and Marslen-Wilson 1995) and were basic-level taxonomic sisters (e.g., prime: *cat*, target: *dog*), given the 'associative boost' reported in adult priming studies (Moss, Ostrin & Tyler, 1997). Unrelated word-pairs shared no semantic or associative relationship, and no phonological onset or rhyme (e.g., prime: *plate*, target: *dog*). Similarly, distracters shared no phonological, semantic or associative relationship with prime or target (e.g., distracter: *boat*). Within a stimulus list, half of the primes were related and half unrelated, and no stimulus was repeated. The priming conditions are illustrated in Figure 1.

Visual stimuli were high quality digital photographs, selected as typical exemplars of targets and distracters by a native speaker of English, whose typicality was confirmed by two native speakers of British English. Pictures were presented on a 10% grey background. Audio stimuli were created in a single recording session, in a sound-attenuating booth on DAT tape sampling at 44.1 kHz. A minimum of three tokens of

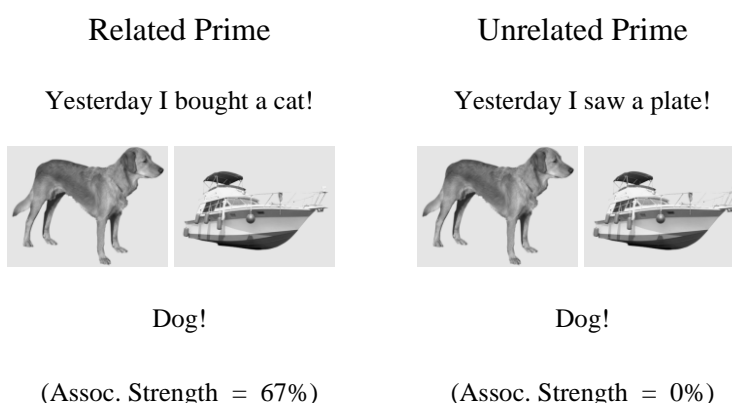


Figure 1. A yoked picture-pair in 2 priming conditions. Association strength from the Birkbeck Word Association Norms (Moss and Older 1996)

each auditory stimulus were produced by a female native speaker of British English, using high-affect child directed speech. The single best token of each stimulus was manually selected for clarity, typicality and affect, and edited to remove head and tail clicks. Auditory priming phrases had a mean duration of 2150 ms ($SD = 187$ ms). Auditory targets had a mean duration of 551 ms ($SD = 120$ ms).

Procedure

After a few minutes of 'settling in' in a dedicated play room, infants sat on their caregiver's lap facing a back-projection screen in a purpose built IPL booth. Caregivers were asked to wear headphones and to close their eyes during the procedure, which lasted approximately one and a half minutes. The experimenter moved to an adjacent control room, where each trial was manually initiated when the infant's attention was centred on the screen. While the screen was blank, the priming phrase began (e.g., *Yesterday, I saw a cat!*), followed by an inter-stimulus interval (ISI) of 200 ms, then the target word in isolation (e.g., *Dog!*). Presentation of target and distracter pictures began at a stimulus onset asynchrony (SOA) of 200 ms or 400 ms from the onset of the target word, depending on participant group. Picture pairs remained onscreen for 2,500 ms. Each infant saw 12 trials from a single stimulus list. Trial order was randomised on presentation. Target side was counterbalanced. Infants sat approximately 90 cm from a screen with a display area 79 cm wide. Pictures were 32 cm wide. Together they occupied a visual angle of approximately 48° , separated by a gap of 15 cm (10°).

Timing. In adult priming studies, a distinction is often made between 'automatic' and 'strategic' priming (for overview, see McNamara 2005). A short prime-to-target ISI was employed to capture the early stages of spreading activation. Moss, Ostrin, Tyler & Marslen-Wilson's ISI of 200ms (1995) was selected, on the grounds that infants' phonological processing speed is

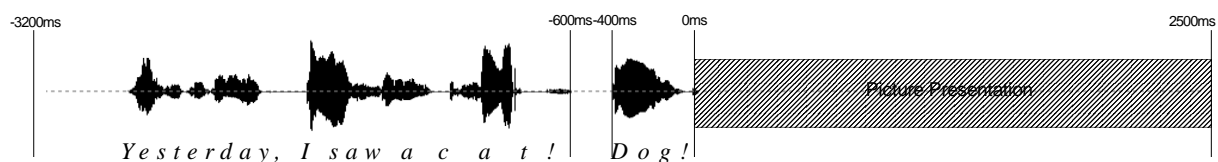
similar to adults' (Swingle, Pinto & Fernald, 1999). Previous studies have demonstrated that infants as young as 18 months-of-age can extract sufficient acoustic information from the first 300 ms of a word to correctly identify its referent in a free-looking task (Fernald, Swingle and Pinto 2001). Two target-to-test stimulus onset asynchronies (SOAs) were selected. A 'long' SOA of 400 ms was selected for one group of infants, to ensure that prior to picture presentation infants had heard sufficient phonological information to correctly identify the named picture. A shorter SOA of 200 ms was selected for the second group of infants, to increase the task difficulty, and thereby, the automaticity of the task. Trial time-courses for the two SOA groups are illustrated in Figure 2.

Scoring & Measures

Infants' eye movements were monitored by small cameras located above the two picture areas, and combined into a split-screen picture by a video mixer. Recordings were digitally captured during test. Blind manual coding was conducted offline frame-by-frame at a temporal accuracy of 40 ms. Coding was conducted by an experienced coder (previously assessed inter-coder reliability: $r(48) = 0.97$, $p < 0.001$). Looks to left and right were coded from the onset of the pictures, and later re-combined with trial information using software which converted fixation data into values for target and distracter. Both large- and small-scale timing measures were calculated: one macro-level measure assessed the relative preference represented as $T / (T + D)$ for the named target picture during the course of the whole trial, and one micro-level measure of reaction time (RT) assessed the speed of infant eye-movements.

Macro-measure: The proportion of target looking (PTL) is the total amount of time spent looking at the target (T) as a proportion of the total amount of time spent looking at both pictures (T + D). It can be This measure represents relative picture interest over the whole picture presentation period (2500 ms), excluding

Long SOA (400ms)



Short SOA (200ms)

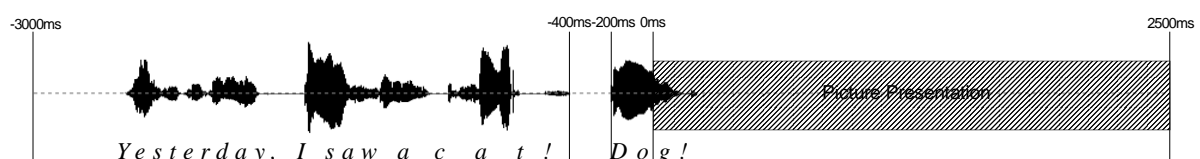


Figure 2. Trial timing. Origin (0ms) indicates the onset of the test-phase of the trial, when pictures are presented on the screen. Wave-forms from actual stimulus tokens, as produced by GoldWave visual waveform editing software (1995, v5.10).

time spent switching between pictures, blinking, or looking away from the screen area.

Micro-measure: Time-to-disengage is an RT measure which describes the amount of looking time taken to initiate a *saccade away from* the first fixated picture. Time-to-disengage is a *dynamic* measure of reaction time, with the measurement beginning at the fixation of the first picture. This measure is equivalent to the duration of the first fixation. Timing windows for analysis of RT measures were established using the visual inspection method described in detail by Canfield and colleagues (1997).

The 'linking hypothesis' for the macro-level measures is this: If infants distribute their fixations randomly between pictures for the duration of the trial, then relative measures assessing looking over the test phase would 'even out' across trials, creating means of similar value for target and distracter pictures. However, if the name of the picture induces a systematic visual preference for named targets over unnamed distracters, then the pattern of behaviour is consistent with infants mapping spoken words to target pictures. Within this framework, the current study seeks to identify systematic differences in looking behaviour when *the same target* is presented in one of two verbal contexts (related prime, unrelated prime). As argued by Aslin (2007), the duration of accumulated fixations is difficult to interpret (does more looking imply continuous interest, effortful processing, or blank staring?). For this reason, the micro-structure of the trial is also valuable, as it provides a measure of rapid responses to suddenly appearing stimuli and to particular stimulus combinations. If RT measures vary systematically according to the priming condition, it informs our understanding of the ease and speed of linguistic processing under different lexical conditions. A priming effect caused by online processing demands would support a model of lexicon development which features inter-connectivity at an early stage

Results

According to the British CDI collected at the time of test, the mean receptive CDI score for 18-month-olds was 197 words ($SD=65$) out of a possible 416. Twenty-four-month-olds had larger vocabularies than 18-month-olds ($Z(71, 63)=7.91, p<0.001$), with a mean of 318 words ($SD=67$). At 24 months-of-age there was no difference in the vocabulary sizes of the two SOA groups. At 18 months-of-age, participants in the short SOA group (200 ms) had larger vocabularies than those in the long SOA group (400 ms) ($Z(33, 30)=1.95, p=0.05$). This between-group difference did not create any difference in 18-month-olds' looking behaviour¹, nor did it affect the number of test items known by the two SOA groups. Eighteen-month-olds were reported to understand a mean of 9 of the 12 primes words ($SD=2.5$) and 10 of the 12 target words

($SD=2.2$). Twenty four-month-olds were reported to understand a mean of 11 primes ($SD=1.4$) and 11 targets ($SD=1.2$).

In order to test for relationships between those words which were encoded in the lexicons of individual infants, only trials in which both the prime and target word were reported as 'understood' were included in analyses. For 18-month-olds, 253 trials were thus excluded from the original 756, leaving 67% of trials available for analysis. With larger vocabularies, the 24-month-olds lost fewer trials to this exclusion criterion, with 91% of original trials available for analysis (78 of 852 trials excluded). Analyses were conducted separately for each age group due to the greater variance predicted in the 18-month-old data. Trials in which infants did not fixate the picture areas of the screen were also unanalysed, accounting for a further 3% of trials. For RT measures, 283 of the remaining trials (23%) were removed from analysis given that the infant looked to one side of the screen prior to the onset of pictures.

Participant means for the proportion of target looking were calculated separately in each priming condition. The direction of the first fixation was monitored, and was treated as an independent variable in the RT measure. According to the most stringent guidelines for analysis of counterbalanced experimental designs, the list of words sharing a priming condition in each subject group is included as a factor in analysis (Raajmakers 2003; Raajmakers, et al. 1999).

18-month-olds

Figure 3 depicts the proportion of target looking for each SOA group, with the priming conditions plotted separately. 18-month-olds demonstrated a general preference for the named target picture over the unnamed distracter picture (see Figure 3), consistent with previous findings that 18-month-olds show target preference for named objects following the onset of a label (Reznick 1990). In a three-way ANOVA comparing the effect of SOA group (long, short), prime condition (related, unrelated) and stimulus list (*horse, dog*), on PTL, only stimulus list systematically affected 18-month-olds' looking behaviour, as indicated by a significant main effect ($F(1, 113)=20.24, p<0.001$, partial $\eta^2=0.15$). This finding demonstrates that stimuli in one list attracted more looking overall, but neither the SOA group nor the priming condition systematically affected overall looking preference for 18-month-olds.

Time-to-disengage is plotted in Figure 4, with direction of first fixation and priming condition shown separately. Within the analysis window of 120 ms to 1600 ms, first looks to targets were disengaged from significantly slower than first looks to distracters. This finding is consistent with the previously reported finding that unnamed distracter pictures are rejected faster than named target pictures (Fernald, et al. 1998; Swingley, et al. 1999). Time-to-disengage was assessed separately for each look direction in two-way

ANOVAs comparing the effect of prime condition (related, unrelated) and stimulus list (*horse*, *dog*). Stimulus list was the only significant source of variance for 18-month-olds, as indicated by main effects (target direction: $F(1, 83) = 6.01$, $p < 0.05$, partial $\eta^2 = 0.07$; distracter direction: $F(1, 92) = 6.77$, $p = 0.05$, partial $\eta^2 = 0.07$). Neither the SOA group nor the priming condition generated a systematic effect on reaction time for 18-month-olds.

The findings in both measures indicate that 18-month-olds demonstrated target discrimination, with faster rejection of distracter pictures, and overall preference for named targets, even though the task was quite fast paced, and infants were not given 'familiarisation time' prior to labelling. Looking behaviour for this age group was affected by stimulus variation between the two stimulus sub-lists. In particular one sub-list generated significantly more target looking in the macro-level measure. 18-month-olds showed no evidence of being affected by the priming condition, or by the timing variation. A vocabulary-matched sub-sample of 18-month-olds produced the same pattern of results as reported in the main analysis, and is omitted for brevity.

24-month-olds

In proportion of target looking (PTL), 24-month-olds showed significantly greater looking to the named target than to the unnamed distracter (see Figure 3). A three-way ANOVA compared the influence of SOA group (long, short), prime condition (related, unrelated), and stimulus sub-list (*horse*, *dog*) on PTL. A significant effect of priming condition was evident ($F(1, 134) = 15.66$, $p < 0.001$, partial $\eta^2 = 0.11$), along with a significant effect of stimulus list ($F(1, 134) = 31.13$, $p < 0.001$, partial $\eta^2 = 0.19$). There

were no further effects or interactions, indicating that the priming effect was not influenced by the stimulus group. As is clear in Figure 3, target preference in the related prime condition was significantly higher than in the unrelated priming condition. This finding indicates that this standard measure of target recognition was *enhanced* when the named target was preceded by a related word, relative to when it was preceded by an unrelated word. Like younger infants, 24-month-olds showed greater preference for named targets in one stimulus sub-list than the other ($t(140) = 5.14$, $p < 0.001$, $d = 0.87$).

Time-to-disengage (analysis window of 120 ms to 1600 ms) was significantly slower when the first fixated picture was the target than it was when the first fixated picture was the distracter (see Figure 4). Like younger infants, the older age group rejected recently fixated pictures faster when the picture mismatched the unfolding label. Time-to-disengage in each look direction was subjected to a three-way ANOVA comparing the influence of SOA group (long, short), priming condition (related, unrelated) and stimulus sub-list (*horse*, *dog*). In trials with first looks to the target there was a significant main effect of prime condition ($F(1, 184) = 5.13$, $p < 0.05$, partial $\eta^2 = 0.03$). Time-to-disengage from targets was significantly slower in the related prime condition, than it was in the unrelated prime condition (see Figure 4). In trials where the first fixation was to the distracter, a tendency was evident in the main effect of prime condition ($F(1, 137) = 3.17$, n.s., partial $\eta^2 = 0.02$). Although the effect was not significant, the p -value of 0.08 approached the alpha-level of 0.05, indicating a moderate trend. The findings from time-to-disengage demonstrate that when the target was preceded by a related prime, infants tended to reject distracter pictures *even faster* and reliably

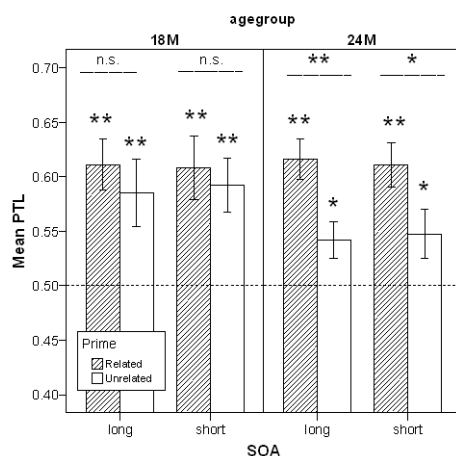


Figure 3. Proportion of target looking (PTL) according to age, SOA group and priming condition. Dashed horizontal line indicates chance value of 0.5. One sample t -tests comparing mean value to chance are marked above each bar. Independent samples t -tests comparing means for each priming condition are marked above pair. ** $p < 0.01$, * $p < 0.05$. Whiskers show \pm one standard error.

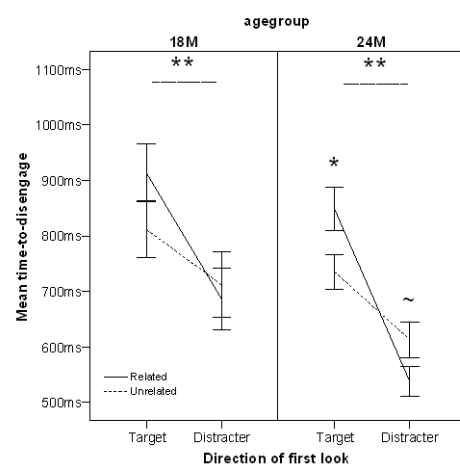


Figure 4. Time-to-disengage according to age, direction of first look and priming condition. Wilcoxon's rank sums tests are marked at the top of each plot for look direction and above each comparison for priming condition. ** $p < 0.01$, * $p < 0.05$, ~ $p < 0.10$. Whiskers show \pm one standard error.

fixated target pictures *even longer*. This finding effectively shows enhanced target discrimination in the related condition, as can be seen in the steeper slope of the line representing the related prime condition in Figure 4. No effect of SOA group or stimulus sub-list were observed in the analysis of time-to-disengage.

The findings from both measures show that, like 18-month-olds, 24-month-olds were able to identify a named target picture from a pair of pictures in a fast-paced referent identification task, as indicated by their faster rejection of distracter pictures and their overall preference for named targets. Unlike 18-month-olds, older infants also showed an effect of priming condition. In both measures, the degree of target recognition was effectively enhanced in the related prime condition, relative to the unrelated prime condition. This finding is consistent with a semantic system which encodes relatedness between word meanings. While stimulus list effects were observed in the macro-level measure, they were not observed in the reaction time measure.

Developmental Trajectory

Figures 3 and 4 suggest that infants in both age groups tended to show the same general pattern of responses (lower target preference in the unrelated condition, greater difference between RTs in the related condition), but the effect of the prime was only reliable in the older age group. This priming effect could be interpreted as evidence that semantic relatedness emerges between 18 and 24 months-of-age. However, as the difference between conditions was smaller and more variable in younger infants, it could also mean that younger infants' greater variability was responsible for the lack of priming effect. Given that younger infants lost more trials to the lexical exclusion criterion, this interpretation is quite likely.

Another way of approaching the difference between age groups is to establish whether the differences in

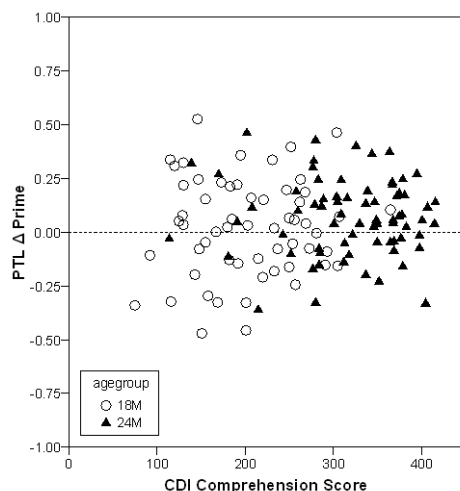


Figure 4. Primed PTL plotted against individual CDI comprehension score, with age groups marked separately. Each point represents an individual participant. Chance value (0 difference) indicated by horizontal dashed line.

performance are associated with age-based changes or with vocabulary size *per se*. If infants with larger vocabularies show larger priming effects, this could be taken as evidence of changes in lexicon structure over development. To investigate this possibility, mean PTL in each condition was used to calculate a difference measure for each individual. This measure can be represented as: $\Delta\text{-prime} = \text{PTL}_{(\text{related})} - \text{PTL}_{(\text{unrelated})}$. In this measure, a value of zero would indicate no difference between priming conditions, and a positive value would indicate more looking to targets in the related prime condition. In Figure 5, $\Delta\text{-prime}$ is plotted against CDI comprehension score for infants in both age groups. In this plot it is clear that the total CDI scores of the two age groups overlap substantially. The spread of the $\Delta\text{-prime}$ scores is broad (ranging from 0.5 to -0.5), with the majority of infants showing the expected priming effect ($\Delta\text{-prime}$ above chance). Younger infants show greater variance in $\Delta\text{-prime}$. No linear trend was evident between total vocabulary size and individual primed PTL either at the overall level, or within age group. The same pattern was found in a difference measure for time-to-disengage, which is omitted for brevity. These comparisons demonstrate that the size of the lexicon did not predict the magnitude of the priming effect across the second half of the second year.

Discussion

This research was motivated by an unresolved question in the lexical development: When do infants encode relationships *between* the meanings of the words they are learning? And are early lexicons structured differently? While network models of development suggest that lexicon organisation does not change throughout development, there is little behavioural data to confirm whether this account is correct. A new method was devised, which combined the prime-target auditory presentation sequence of adult priming tasks with the implicit, infant-friendly referent-identification task of IPL.

The primed IPL task was designed to mimic adult sequential priming tasks in an infant-friendly context, by replacing lexical decision with a period of free-looking. Picture pairs were displayed following the auditory presentation of two words, whose relationship and timing could be manipulated. Given the high speed of stimulus presentation, and the potentially confusing priming phrase, it is noteworthy that infants at both ages demonstrated reliable target identification in macro- and micro-level measurements. While there was some variation in the degree of comprehension demonstrated across items, the general finding of target discrimination in both age groups indicates that the current task effectively taps into the comprehension skills of 18- and 24-month-olds infants.

In addition, differences between the two priming conditions were observed in the older age group, in

both micro- and macro- level measures of looking behaviour. 24-month-olds fixated targets longer, and showed more overall target interest when the target was preceded by a related word. This constitutes a clear 'priming effect', indexing the effect of the prime word on looking to the target; Infants who heard *cat* before *dog* showed greater comprehension of the *dog* than infants who had just heard *plate*. Priming was unaffected by the general effects of stimulus interest, and was consistent with the model of an interconnected lexicon.

Stimulus Controls.

Two stimulus controls were considered critical for primed IPL. First, in order to avoid inadvertent memory effects which might interfere with priming, no stimuli were repeated within a testing session. Secondly, and perhaps most importantly, only those trials in which infants were reported to understand both the prime and the target were included in the analysis. This approach is advocated by McNamara (2005) in situations where testing periods are relatively short.

Furthermore, at the experimental level, the inclusion of unknown words would generate a pattern of noise which is likely to mask genuine priming effects: If a prime or a target is not understood in a 'related' trial, that trial effectively becomes 'unrelated,' as only one word shares a relationship with the named picture. Yet if a prime in an 'unrelated' trial is not understood, the trial remains 'unrelated' (with one word sharing a relationship with the target). This skew would reduce the difference between the two trial types, potentially masking legitimate priming effects. Eliminating this confound is particularly relevant for infants with small vocabularies, for whom this noise would be greatest. Despite valid concerns about the validity of parental report of comprehension (Tomasello and Mervis 1994), recent research has demonstrated that parental report can reliably predict which items will attract lexical comprehension in IPL tasks at 18 months-of-age (Styles and Plunkett In Press). Parental report was therefore chosen as the most appropriate exclusion criterion, for testing relationships between only those words which were known to the infant.

Semantic Organisation and Processing

In the experiment reported here, priming could have been produced by one of three processing effects: spreading activation between word representations enhancing processing of the target word in the related condition; spreading activation to unrelated areas of the lexicon inhibiting processing of the target word in the unrelated condition; or by noticing the overlap between the internal representation of the prime and the picture of the target. The first two processing accounts are explicitly 'lexical', as they rely on the presentation of both words to create the enhanced interest in the target picture. The latter could be termed predominantly 'visual,' as the mental representation of the word *cat*

might allow infants to perform a similarity judgement on the subsequently presented picture of a dog, regardless of whether the target word was presented.

Models of the adult lexicon provide different accounts for the effects of priming, and whether visual features form an integrated part of the semantic system for adults. In classical spreading activation models (Anderson 1983; Collins and Loftus 1975), each word is envisaged as an independent node. Activation can only flow between words which are connected in the network. On the other hand, in distributed network models (e.g., Cree and McRae 2003; McRae, et al. 1997), each word is envisaged as a pattern of activation across a number of nodes. All nodes are interconnected, but some connections are stronger than others, allowing activation to flow more efficiently from one pattern of representation to another. The main theoretical difference between these models is that the classical spreading activation model encodes each word separately, while in distributed models, words with similar meanings also have similar representations. This means that distributed models can account for priming in the absence of typical associative relationships, and can also account for errors based on visual similarity. According to the distributed account of spreading activation, the fact that infants can perform a similarity judgement after hearing the word *cat* demonstrates that the lexicon has encoded those visual features. In this account, both spreading activation and visual overextension are evidence of integration in the developing lexicon. By way of contrast, compare the alternative that early lexicons encode difference at the expense of relatedness, with maximally differentiated representations for each known word. If this were the case, hearing *cat* before *dog* would not be expected to affect infants' performance in the referent identification task.

Additional support for a more traditional lexical connectivity account comes from a recent study, reported by Styles, Arias-Trejo and Plunkett (2008). The study (Experiment 3) was similar in design to the experiment reported here, with the exception that targets were only named in half of the trials. In addition, to increase the difficulty of the task, targets and distracters were selected to share phonological onsets, making them cohort-competitors during the early stages of lexical access. After hearing a related prime, 21-month-olds tested in this experiment failed to show greater interest in the target without the additional 'support' of the target label; They showed robust target recognition *only* in the condition where the target was both named and primed by a related word. This finding suggests that priming effects in IPL rely on spreading activation at the lexical level of representation, not on extra-linguistic visual matching processes.

These findings from primed IPL supplement the infant ERP findings of Friedrich and Friederichi (2004; 2005a; 2005b) and Torkildsen and colleagues (2007), by demonstrating that semantic relatedness not only

causes differences in brain signals, but has a behavioural outcome in a simple language processing task. These behavioural data also support the continuous lexicon development trajectory predicted by the mathematical network modelling of Styvers and Tenenbaum (2005), and the longitudinal network models of Hills and colleagues (2008); The semantic relationships predicted by these models are shown to have a behavioural effect on language processing by the end of the second year. Furthermore, the demonstration that vocabulary size does not predict the degree of the priming effect is also consistent with a model of continuity in lexicon development.

These findings suggest that infants integrate each word they learn into a complex, adult-like semantic system which encodes relatedness between words. Having demonstrated a new method for investigating early semantic relationships, it remains to be seen which kinds of relationships are the most strongly encoded for infants. In the current experiment prime-target pairs were selecting which shared both semantic and associative relationships, in order to maximised the likelihood of an associative 'boost' (Moss, Ostrin, Tyler and Marslen-Wilson 1995). It remains to be seen whether taxonomy or association provides a stronger source of relatedness in the infant lexicon. Other relationships which may be encoded at different stages in development include functional relationships, script-based relationships, and abstract semantic features. Further experimental work will be needed to clarify exactly how adult-like the infant semantic system is, and whether different kinds of relationship are weighted differently across development.

Another issue which remains to be it is explored is *how well* a word needs to be known before it is integrated into the semantic system. All of the relationships tested in the current study were words reported as 'understood' by the infants' parents. Previous research has demonstrated that British parents set a fairly high comprehension threshold in vocabulary surveys – selecting only those words which are well enough known to reliably generate target discrimination in a relatively difficult IPL task (Styles and Plunkett In Press). It is therefore unclear whether semantic integration might only be evident for words which are very well known, or whether semantic integration occurs during the earliest stages of 'fast mapping' a word to a referent. Following the trajectory of newly learned words would provide valuable insights into the process of word learning and general lexicon development.

Conclusions

By the end of the second year, infants' performance in a referent identification task shows that their semantic system encodes relatedness between known words. For 24-month-olds, the relatedness of an auditory prime significantly affected their looking behaviour in both micro- and macro- level measures of

lexical comprehension. This primed pattern of responding is consistent with a model of a developing lexicon which is interconnected even in its early stages. At this stage it is unclear whether the priming effects observed in the older age group are due to spreading activation between closely related nodes, or to overlapping representations of each word's meaning. However, the primed response pattern is consistent with a model of the lexicon which encodes semantic relatedness from an early stage, and is not consistent with a model in which each word's meaning is maximally differentiated from the meanings of all other words. It remains to be seen whether one type of relationship (associative or taxonomic) is the source of organisational structure in the infant semantic system, or whether an adult-like mix of relationships is encoded. Below 24 months-of-age, robust priming effects were not observed, it is possible that the semantic system may begin to re-organise at about this time. However, the continuity of performance across the vocabulary range suggested that the different performance of the age groups may have been due to the sensitivity of the task.

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Appendix

List of Primes, Targets & Distracters

List A

Prime & Carrier	Target	Distracter	Prime Type	WA-Strength ^a
Yesterday, I saw a cat	Dog	Boat	Related	66.7
Yesterday, I saw a sheep	Cow	Toast	Related	13.3
Yesterday, I ate ^b an apple	Banana	Lion	Related	2.4
Yesterday, I bought a boot	Shoe	Bread	Related	30.0
Yesterday, I bought a plate	Cup	Pushchair	Related	25.2
Yesterday, I bought a cot	Bed	Chicken	Related	9.5
Yesterday, I saw a train	Horse	Sock	Unrelated	0
Yesterday, I saw a lorry	Mouse	Table	Unrelated	0
Yesterday, I saw an elephant	Cake	Trousers	Unrelated	0
Yesterday, I bought a hat	Bus	Monkey	Unrelated	0
Yesterday, I saw a pig	Car	Bowl	Unrelated	0
Yesterday, I ate ^b a biscuit	Coat	Bear	Unrelated	0

List B

Prime & Carrier	Target	Distracter	Prime Type	WA-Strength ^a
Yesterday, I bought a plate	Dog	Boat	Unrelated	0
Yesterday, I bought a boot	Cow	Toast	Unrelated	0
Yesterday, I bought a cot	Banana	Lion	Unrelated	0
Yesterday, I saw a cat	Shoe	Bread	Unrelated	0
Yesterday, I bought a sheep	Cup	Pushchair	Unrelated	0
Yesterday, I ate ^b an apple	Bed	Chicken	Unrelated	0
Yesterday, I saw a pig	Horse	Sock	Related	2.1
Yesterday, I saw an elephant	Mouse	Table	Related	8.9
Yesterday, I ate ^b a biscuit	Cake	Trousers	Related	4.8
Yesterday, I saw a train	Bus	Monkey	Related	6.2
Yesterday, I saw a lorry	Car	Bowl	Related	4.8
Yesterday, I bought a hat	Coat	Bear	Related	12.5

^a Forward Adult Word Association norms from Moss & Older (1996)

^b Semantically restrictive verb