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Prime saliency in semantic priming with 18-month-olds☆

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ABSTRACT

This study investigated semantic priming in 18-month-old infants using the inter-modal priming technique, focusing on the effects of prime repetition on saliency. Our findings showed that prime repetition led to longer looking times at target referents for related primes compared to unrelated primes, supporting the existence of a structured semantic system in infants as young as 18 months. The results are consistent with both Spreading Activation and Distributed models of semantic priming. Additionally, our findings highlighted the impact of prime-target stimulus onset asynchronies (SOAs) on priming effects, revealing positive, negative, or no priming effects depending on the chosen SOA. A post-hoc explanation of this finding points to negative priming as a possible mechanism. The study also demonstrated the utility of the inter-modal priming task in studying lexical-semantic structure in younger infants with its diverse measures of infant behaviour.

1. Introduction

In lexical decision or naming tasks, adults will respond faster to a target word, e.g., ‘doctor’, if it is preceded by a related word, e.g., ‘nurse’. ‘Nurse’ is considered to **prime** ‘doctor’, providing evidence that the prime and target words are connected in the adult mental lexicon (Meyer & Schvaneveldt, 1971; Tulving & Schacter, 1990).

The size of the priming effect is determined by a multitude of factors including[1]:

- the type of relationship between the prime and target. Are they phonologically related, taxonomically, thematically or associatively related or some combination thereof?
- the strength of the relationship between target and prime.
- the inter-stimulus interval (ISI) between target and prime.
- the nature of the task in which the prime is embedded.
- the modality of presentation of both prime and target.
- the frequency of occurrence of the prime and target, both external to the priming event and within the priming experiment itself.
- the clarity (visual or auditory) of the prime and target stimuli themselves.

The impact of these factors on priming are themselves often used as clues to infer the nature of the processes and representations characterizing the mental lexicon. For example, it is often reported that prime/target pairs which are associatively or thematically related result in longer-lasting priming effects than pairs which are taxonomically related (Joordens & Besner, 1992; McNamara, 2005; Moss, Ostrin, Tyler, & Marslen-Wilson, 1995; Murphy & Hunt, 2013; Seidenberg, Waters, Sanders, & Langer, 1984; Shelton & Martin, 1992). This differential impact of ISI on different types of semantic relationships has been used to argue for distinct types of connections between taxonomically and associatively related prime/target pairs (Plaut, 1995; Plaut & Booth, 2000). Similarly, double dissociations in aphasic patients exhibiting taxonomic priming but not associative priming effects or *vice versa* (Kalénine et al., 2009; Mirman & Graziano, 2012; Mirman, Landrigan, & Britt, 2017; Schwartz et al., 2011) have been used to argue for distinct processes and representations underlying taxonomic and thematic semantic memory (though see Rogers et al., 2004 for an alternative perspective). Enhanced priming for targets that are low frequency or visually or auditorily degraded point to an activation-based account of semantic priming (e.g., McNamara, 2005). In general, understanding how the factors that influence semantic priming achieve their effects has proved important for gaining insights into the structure of the mental lexicon.

The structure of the mental lexicon in toddlers has also been investigated via experimental priming studies. These studies typically consist of an item being presented as a ‘prime’ to the child. This may be in

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[1] This list is not intended to be exhaustive but highlights some of the most frequently investigated factors in the extensive priming literature. Readers are referred to reviews, such as Hutchison (2003), Lucas (2000), McNamara (2005) and Neely (1991), for more comprehensive coverage.

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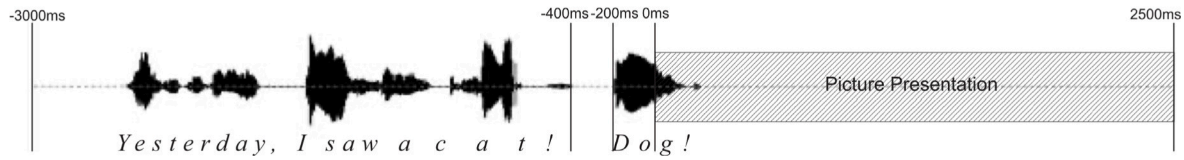

Fig. 1. Schematic for timing of the toddler auditory priming task. See text for further explanation.

the form of an image representing the referent of that word without an associated label (e.g., Mani & Plunkett, 2010, 2011), or the word being presented in auditory form as a label without an associated image (e.g., Arias-Trejo & Plunkett, 2009, 2013; Styles & Plunkett, 2009). The prime is intended to elicit the toddler's representation for that item. Immediately following the presentation of the prime to the toddler, they are presented with an auditory 'target' stimulus together with a pair of images, one of which depicts the target referent (see Fig. 1). For some trials, the target item is related to the prime while on other trials the prime and target are unrelated. It is assumed that a related prime pre-activates the target word, facilitating identification of and attention to the target image, as compared to an unrelated prime. To illustrate, in Arias-Trejo and Plunkett's (2009) semantic priming study with 18- and 21-month-olds, the prime was presented in auditory form without an associated image (e.g., 'cat'). For half of the trials, the target item (e.g., 'dog') belonged to the same superordinate-level category as the prime. For the remaining trials, the prime was unrelated to the named target. The experimenters hypothesized that toddlers would attend more to the dog in related trials than in unrelated trials because the prime 'cat' is likely to pre-activate it. Toddlers' attention towards the target and distractor pictures was evaluated by means of a preferential looking task, using eye-tracking to measure which item toddlers attend to more via their gaze behaviour. Arias-Trejo and Plunkett's (2009) hypothesis was confirmed: 21-month olds looked longer at the target object in the related condition as compared to the unrelated condition. However, 18-month olds were equally likely to fixate the target image in the related and unrelated conditions, i.e., there was a *priming effect* at 21-months but not at 18-months of age. Arias-Trejo and Plunkett (2009) concluded that by 21-months of age, toddlers have begun to organize their vocabulary into a *semantic system* that highlights the meaning relations between words, as attested by the capacity for, say, 'cat' to prime 'dog'. The absence of any priming effects at 18-months of age led Arias-Trejo and Plunkett to speculate that these younger infants lack a structured semantic system and that word meanings are most likely represented independently of each other, a status they called the *lexical island hypothesis*.

Around 18 months of age, toddlers enter the so-called 'vocabulary spurt'—a period of rapid quantitative increase in vocabulary development (e.g., McMurray, 2007; McShane, 1979; Plunkett, 1993). This increased number of lexical items calls out for a more systematic method of storage in semantic memory to make future word acquisition and speech processing as efficient as possible. It is perhaps therefore unsurprising that there appears to be a transition to a structured lexical-semantic system around the time of the vocabulary spurt.

Connections between words based on co-occurrence data (CHILDES database) have been found in the lexicons (based on parental report measures of vocabulary knowledge) of toddlers (Hills, Maouene, Maouene, Sheya, & Smith, 2009; Hills, Maouene, Riordan, & Smith, 2010) and infants as early as 15 months (Beckage, Smith, & Hills, 2011). However, observing active connections via experimental procedures at such a young age has proved more challenging. Sensitivity towards semantic word links has been observed in 18-month-olds using a head-turn preference procedure (Delle Luche, Durrant, Floccia, & Plunkett, 2014; Plunkett, Delle Luche, Hills, & Floccia, 2022). These studies showed that toddlers preferred to listen significantly longer to lists of words from the same semantic category compared to listening to lists of words from mixed semantic categories. The authors interpreted these results as the toddlers not only recognizing the individual words in the lists but also infer the connection between them, thereby demonstrating sensitivity to the meaning of the words in the list being from the same semantic category. The Plunkett et al. (2022) study also demonstrated that manipulating the ISI between the words in the lists had a differential impact on the priming of different types of semantic relations: long ISIs (800 ms) abolished priming for words that were only taxonomically related whereas priming was maintained for words that were associatively related. This finding suggested that the links between words that are taxonomically related may function in a different way to those that are associatively related in the infant mental lexicon, perhaps in a manner reminiscent of the adult mental lexicon.

The Delle Luche et al. and Plunkett et al. studies are, however, quite different to the procedure that is more commonly used to assess lexical links in toddlers' lexical-semantic systems. In the semantic priming study by Arias-Trejo and Plunkett (2009), 18-month-olds' performance was compared with that of 21-month-olds'. Eighteen-month-olds failed to show any evidence of priming, in that they were just as likely to look towards the target item significantly more than the distractor on trials in which the prime was semantically related to the target as in trials where the prime was semantically unrelated. Twenty-one-month-olds, on the other hand, did exhibit a priming effect.

While this may bring into question the interpretation of the Delle Luche et al. and Plunkett et al. studies, one must also note the stark differences in the methodologies of the two procedures. As well as requiring attention to both the auditory and visual modalities, the inter-modal priming studies may place more of a burden on working memory than the head-turn procedure. In the former, the toddler must not only compute the relationship between the prime and target words but she has to demonstrate sensitivity to that relationship by identifying a target referent. In the head-turn preference procedure, there is no requirement to identify a target referent. Furthermore, in addition to the extra task the toddler has to perform with the inter-modal priming paradigm, the extended number of words from the same category presented in the head-turn preference procedure may make the category more salient thus making it easier to activate. In contrast, in the inter-modal priming studies, the semantic category may not be as salient as the prime is only presented once. The study reported in the current paper explores the possibility that prime repetition may increase the saliency of the prime as a stimulus to pre-activate the target.

Auditory-only semantic priming has also previously been observed in 24-month-olds (Willits, Wojcik, Seidenberg, & Saffran, 2013). In the Willits et al. study with 24-month-olds, using the head-turn preference procedure, the auditory stimuli were presented in repetition. That is, stimulus items (e.g., "dog…dog…dog") were either followed by presentation of semantically related items in repetition (e.g., "kitty…kitty…kitty") or unrelated items in repetition (e.g., "juice…juice…juice"). In this study, listening times for the related repeated lists were shorter than for the unrelated repeated lists, again demonstrating evidence for auditory priming. In this study, the saliency of the prime is clearly accentuated through repetition.

It is very likely that, as toddlers are acquiring new words at such a rapid rate, their lexicons are in need of continual consolidation and updating, making them fragile and prone to interference and lexical competition. Thus, it may take an increased effort for their lexical items to be selected and for the categories of lexical items to be activated, in comparison to older children for instance who have larger vocabularies and greater experience with language. In inter-modal priming experiments, perhaps the single presentation of the prime is insufficient to activate a semantic category so that priming effects manifest as increased looking to semantically related objects in younger toddlers. Hence, we explore whether making the prime more salient to younger toddlers will benefit category activation.

Existing theoretical frameworks on lexical organization are generally agreed on the proposal that the lexicon is structured in a network-like fashion. Due to this interconnected configuration, the retrieval of a word provokes modifications in the accessibility of other associated concepts within semantic memory. Despite varying nuances concerning the arrangement of representations across different models, with spreading activation models advocating discrete conceptual units (Anderson, 1983; McNamara, 2005) and distributed models suggesting that representations are patterns of distributed features (Cree, McRae, & McNorgan, 1999; McRae, de Sa, & Seidenberg, 1997; Plaut & Booth, 2000; Rogers et al., 2004; Rogers & McClelland, 2004), there is a general consensus between these models regarding the network-like character of semantic memory. Both types of model predict that the repetition of a word will result in increased accessibility of related concepts or features within short-term memory, emphasizing the dynamic interaction within semantic networks during word retrieval.

1.1. Present study

The present study revisits the Arias-Trejo and Plunkett study by implementing an inter-modal priming task with 18-month-old toddlers. The study largely replicates the design of the former study. However, the prime phase has undergone several manipulations; the prime presentation was repeated in order to enhance its saliency and, in an alternative condition, it was presented just once, as in the original study. Furthermore, the timing of the prime in relation to the target label was manipulated in the singular presentation condition to determine whether the stimulus onset asyncrony (SOA) between the prime word and the target word affected priming. In the original Arias-Trejo and Plunkett study, the ISI between the offset of the prime word and onset of the target word was held constant at 200 ms. Likewise, the SOA between the onset of the target word and the onset of the visual images was held constant at 200 ms. Styles and Plunkett (2009) manipulated the SOA between the onset of the target word and the onset of the visual images (200 ms or 400 ms) using the same task but found no effect of SOA. It is noteworthy that previous research with adults showed that SOA significantly influences the inhibitory or facilitatory effects observed between related pairs of words during a semantic priming task (Neely, 1991). Shorter SOAs typically result in facilitatory effects; conversely, longer SOAs can lead to inhibitory effects, in which the target word's processing is hindered by the prime (McNamara, 2005). The facilitatory effect can easily be addressed by spreading activation models where the activation is propagated among related concepts (Anderson, 1983; McNamara, 2005). In contrast, the inhibitory effect at longer SOAs is often attributed to the engagement of controlled, effortful processes that attempt to suppress the prime's influence, thereby hindering target word recognition (Neill, 1997). Further, alternative explanations suggest that the inhibitory effects might result from attentional mechanisms, semantic interference, or response competition (Posner & Snyder, 1975; Tipper, 1985).

We predicted that prime repetition would have a beneficial effect on semantic category activation and this would be manifest through differences in target looking on related trials as compared to unrelated trials, akin to the differences in listening times reported by Willits et al. (2013) in their head-turn preference procedure with 24-month-olds. We also expected that varying the SOA between the prime and target words would affect priming, partly because of recent results of a study with 18-month-olds using the head-turn preference procedure showing that the ISI between words in related lists affects listening times (Plunkett et al., 2022), and partly because of the additional memory load caused by longer SOAs. To anticipate, our prediction and expectation were confirmed.

It is also worth pointing out that the inter-modal priming task provides a richer dataset for analysis than the headturn-preference procedure. The latter provides just a single measure for any given trial, i.e., listening time, whereas the former provides continuous eye-tracking information throughout the trial which can be analysed down to the timescale of the time-bins used in the statistical modelling. Insofar as eye-tracking data provides a satisfactory index of the mental processes involved in these priming studies, it is worth pursuing a version of the inter-modal task that can be used with infants at younger ages to investigate the organization and emergence of their lexical-semantic systems.

2. Method

2.1. General procedure

The parents of participating toddlers had previously signed up to the laboratory database and were invited to take part in the study by email. Parents were first sent a vocabulary survey to complete on behalf of their child. Then, parents and their toddlers visited the lab to complete the semantic priming task. Parents received a £5.00 gift voucher as compensation for their time and toddlers were given a t-shirt and certificate. This study received ethical approval (R63335/RE001) from the Central University Research Ethics Committee at the University of Oxford.

2.2. Participants

Thirty-three monolingual 18-month-olds (mean age = 17.93 months, age range = 17 months 16 days to 19 months 8 days, 23 males and 10 females) completed this study. This sample is higher than that expected by the power analysis based on the effect size provided by Arias-Trejo and Plunkett (2009) (δ =.60, α = 0.05, β = .80, n = 24). An additional two participants were excluded from analysis due to fussiness. All participants in this sample were from households where British-English was the primary language. None of the participants were reported by their parents to have any ongoing problems with hearing or vision at the time of participation and none were reported to have been born prematurely.

2.3. Vocabulary survey

Parents of participating toddlers were asked to complete the Oxford Communicative Development Inventory (Oxford CDI; Hamilton, Plunkett, & Schafer, 2000) a few days prior to their visit to the lab with their toddler. The Oxford CDI is a parental report measure of toddler receptive and productive vocabulary containing 418 English words commonly known to English learning toddlers. For each word in the Oxford CDI, parents are required to report whether their child understands (U), understands and says (U/S) or does not understand the word (No).

2.4. Stimuli

Stimulus items were nouns which are found in the Oxford Communicative Development Inventory. According to existing normative data all items were reportedly known by 67%–97% of 18 month-olds (mean 83%, SD 9%). Speech stimuli consisted of recordings from a native female speaker with a southern British-English accent spoken in a child-directed manner. Target and distractor visual stimuli were photographic images presented 500 × 500 pixels, with 2–4 images for each target and distractor item. On each trial, the target and distractor images were presented in a left–right format. A silent, visual attention-getter containing moving cartoon stars was presented during the priming phase.

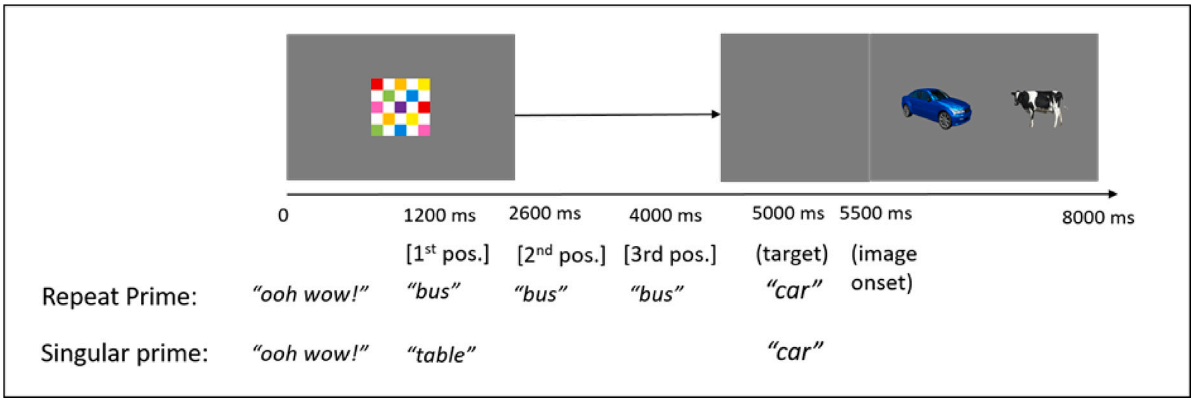

Fig. 2. Schematic for timing of the repeated and singular prime presentation types. See text for further explanation.

2.5. Semantic priming task

The task consisted of 24 trials within which there were six pairings of target and distractor stimuli (Table A.1). For half of the trials, the prime word was repeated three times (e.g., "[boat]" …"[boat]" …"[boat]"), with 500 ms inter-stimulus intervals (ISIs). For the remaining half of trials, the prime word was presented once, in the temporal position of either the first, second, or third repeating prime (e.g., first position: "[boat]" …"[]" …"[]"; second position: "[]" …"boat" …"[]"; third position: "[]" …"[]" …"[boat]"). Singularly presented primes were presented four times in each position (see Fig. 2). All related primes were taxonomically related to the target and several of the related prime-target pairs were associatively related as well.[2] Unrelated primes were neither taxonomically nor associatively related to the targets and distractors. The target and distractor pairings and primes are listed in the Appendix.

Each trial had a total duration of 8000 ms and began with the carrier phrase "Ooh wow!" followed by a silent 200 ms ISI then followed by the first position prime. The audio for the target word was presented 200 ms after the offset of the third position prime (average target word duration: 700 ms). The attention-getter remained on screen during this period until 4800 ms. The visual images for the target and distractor items were presented at 5500 ms and remained on screen for 2500 ms.

Each target-distractor pairing was presented once in the following four conditions: (1) Prime was repeated, prime and target were related ('Repeated-Related'), (2) Prime was repeated, prime and target were unrelated ('Repeated-Unrelated'), (3) Prime was presented once, prime and target were related ('Singular-Related'), (4) Prime was presented once, prime and target were unrelated ('Singular-Unrelated'). Each item in each pair was presented in each role (target or distractor) equally across conditions.

Target and distractor items were from separate semantic categories but shared phonological onset. This control prevented infants from disambiguating the two pictures on the basis of the initial sound of named targets (Mani & Plunkett, 2007; Swingley, Pinto, & Fernald, 1998). The prime words had distinct phonological onsets from target and distractor items to avoid phonological priming (Mani & Plunkett, 2007). No prime was repeated across trials. Trials were presented in a pseudo-randomized order such that there was no consecutive presentation of a particular condition or target-distractor pairing. Target location was also counterbalanced to appear on either the left- or right-hand-side equally.

[2] The degree of associative relatedness of prime-target pairs for individual toddlers is subject to considerable individual variation. See Plunkett et al. (2022) and Fitzpatrick (2023).

2.6. Eye-tracking procedure

Toddlers sat on their parent's lap in a sound-attenuated booth approximately 65 cm from a Tobii TX 300 eye tracker (sampling rate: 120 Hz) which was directly below a 23-inch screen (1920 × 1080 resolution). The task was ran using a custom presentation framework in Matlab based on Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Communication with the Tobii eye-tracker was implemented using the Tobii Analytics Matlab binding from Tobii Analytics SDK 3.0. Prior to the Semantic Priming task, a four-point calibration was performed with a rotating star as the attention-getter. Individual points were recalibrated in order to improve the calibration when required. The background colour of the screen and the visual stimuli were grey. The auditory stimuli were presented through a centrally located loudspeaker. In an adjacent control room, the experimenter controlled the task and initiated trials when the toddler was sitting still and looking towards the screen. The experimenter could monitor the toddler and parent via a video camera and was able to communicate with the parent (if necessary, to fix the toddler's positioning towards the screen position, for example) via a microphone. Parents were instructed to keep their eyes closed during the task and to refrain from interacting with their toddler while the task was being presented. Fig. 3 displays the testing setup.

2.7. Data processing and analysis

Three analyses were performed: overall proportion of target looking, a growth curve analysis (Barr, 2008; Mirman, 2014), and cluster-based permutation analysis (Maris & Oostenveld, 2007). Arias-Trejo and Plunkett's priming study detected priming effects by analysing the proportion of time overall that toddlers spent looking at the target item in related and unrelated conditions. Since the publication of this study, more sophisticated methods of analysing eye-tracking data have been adopted by the field, including growth curve analysis (GCA) (e.g., Mirman, 2014; Mirman, Dixon, & Magnuson, 2008) and permutation/cluster analysis (e.g., Maris & Oostenveld, 2007). Statistical modelling of the time course of gaze data throughout the course of the trial has now been used extensively in infant and toddler studies (e.g., Angulo-Chavira & Arias-Trejo, 2021; Chow, Angulo-Chavira, Spangenberg, Hentrup, & Plunkett, 2022; Chow, Davies, & Plunkett, 2017; Floccia, Delle Luche, Lepadatu, Chow, Ratnage, & Plunkett, 2020). This approach can also be used to analyse inter-modal priming experiments. This involves calculating the proportion of time that toddlers look towards the target on semantically related (prime-target) trials against the proportion of time that they look towards the target on semantically unrelated trials, in consecutive time-bins (usually 100 ms bins) throughout the course of the trial. GCA and/or cluster analyses can then be used to determine whether there are systematic

Fig. 3. Testing booth used in the experiment. See text for further explanation.

differences in the time courses of these preferences in the related and unrelated conditions that might be consistent with a priming effect. It is worthwhile revisiting the design of the original Arias-Trejo and Plunkett study to analyse the time courses of toddlers' gaze data in an inter-modal priming study. An advantage of these more sophisticated statistical methods include a sensitivity to small effects which may well be important for the investigation of infants and toddlers.

Pre-processing of eye-tracking data was conducted using a custom MATLAB script. The minimum fixation duration was set at 100 ms within a radius of 35 pixels. The aggregation of eye-tracking data and track loss analysis were conducted in RStudio (RStudio Team, 2020) using the eyetrackingR package (Dink & Ferguson, 2018). All statistical analyses were conducted in RStudio (RStudio Team, 2020). To reduce inattention effects, all trials with less than 25% attention to the analysis window were excluded, and participants with less than 50% of remaining trials were also excluded. Moreover, for the temporal analysis, the data were aggregated across trials and were binned every 100 ms to reduce autocorrelation (Mirman, 2014). The time window of analysis was from 367 ms to 2490 ms after the picture onset.

In each analysis type, we performed two main comparisons; the first one was to explore the effect of repetition by comparing the trials where the prime was repeated against the trials where the prime was singular. The second comparison was conducted to compare the effect of the timing of singular prime trials.

The overall proportion of looking analysis was performed to permit comparison with previous works. We conducted a binomial logistic mixed effect model using the function *glmer* in R. The dependent variable was the proportion of looking computed by $\frac{T}{T+D}$, where T and D were the looking time towards the target and distractor images over the analysis window, respectively. The fixed factors were dummy coded; in the following explanations, the reference condition will be underlined. For the first comparison, we used relatedness (related, unrelated) and the presentation type (singular, repeated) as fixed factors. The random structure was the maximum that allowed convergence: the slopes of the interaction between relatedness and presentation on the subject. For the second comparison, we included relatedness (related, unrelated) and position (first, second, third) as fixed factors and the slope of relatedness on the subjects as a random factor. To explore the priming effect, a simple contrast was performed only between the related and unrelated conditions using the *emmeans* package. In addition, we conducted a one-sample t-test against chance (0.5) to explore the effect of the prime on the looking behaviour towards the target image.

The growth curve analysis was conducted to compare the temporal dynamics across conditions using a binomial logistic mixed effect model with the function *glmmPQL* from the *MASS* package in R. The dependent variable was the log odds ratio of fixations computed as $\log(\frac{F}{N-F})$, where F is the sum of fixations and N is the total of fixations every 100 ms (Barr, 2008; Mirman, 2014). The time was modelled using linear, quadratic, and cubic orthogonal polynomials (Mirman, 2014). For the first comparison, we used relatedness (related, unrelated) and the presentation type (singular, repeated), and the time terms (linear, quartic, and cubic) as fixed factors, and the slope of the time terms on the subject and the intercept of items as random factors. For the second comparison, we include the relatedness (related, unrelated), position (first, second, third), and the time terms (linear, quartic, and cubic) as fixed factors, and the slope of the time terms on the subject and the intercept of items as a random factors.

Finally, the non-parametric cluster-based analysis was conducted to explore the temporality of priming effects; therefore, we only compared relatedness (related, unrelated) independently for each presentation type (repeated, singular) and each position (first, second, third). We also compared each time series against chance level (0.5) to explore whether participants were looking to the named target. All comparisons were performed with a t-test. The clusters were created using the sum of adjacent *t-values*, and the threshold was set to a *p-value* = 0.05. The permuted distribution of maximum clusters was created by randomly shuffling between conditions or changing the mathematical sign in the chance comparisons (100,000 iterations). Based on this permuted distribution, a cluster was significant if it was higher than 5% of the permutations (two tails).

It is important to note that the validity of GCA in eye-tracking studies has been subject to criticism, particularly concerning the appropriateness of its application relative to the phenomena under investigation and the corresponding experimental design (Huang & Snedeker, 2020). Despite these criticisms, we maintain that GCA is aptly suited for the current research. Aligning with Huang and Snedeker's (2020) methodology, we adhered to several strategic approaches: (1) We strictly utilized predictors that are directly related to our main hypothetical factors, thereby mitigating the risk of Type I error due to multiple comparisons. (2) We employed logistic regression to fit the models, adapting them to the inherent nature of Areas of Interest data instead of adopting a linear approach. (3) By incorporating items as a random effect, we enabled the generalization of results across a diverse item population. (4) We aggregated the data using 100 ms bins to minimize

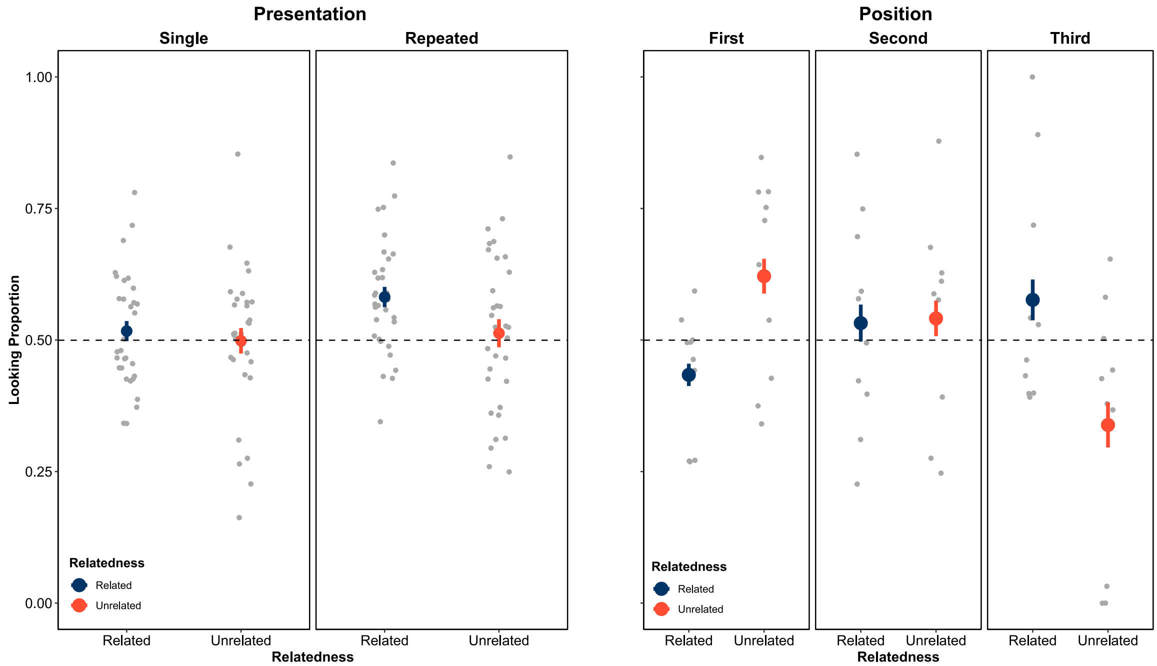

Fig. 4. Overall proportion looking analysis. Note: Grey dots represent individual subjects. Blue and red plots show the mean and standard error. Horizontal dashed lines indicate the chance level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

autocorrelation. Moreover, even though GCA has the potential to yield Type I errors, we supplemented it with a secondary time-course method to assist in corroborating the results. Ultimately, if the phenomena in question do exist, the outcomes of all three analyses should align, each contributing additional insights into the data.

3. Results

3.1. Overall proportion of looking measure

Fig. 4 shows the proportion of looking measures in the presentation type contrast (Fig. 4, left panel) and the position contrast (Fig. 4, right panel). In the presentation type contrast, the results of the binomial logistic model revealed a significant positive slope of the presentation type factor, indicating that toddlers looked more to the related target in the repeated than the singular condition (β = 1.273, SE = 0.554, Z = 2.295, p = 0.021). Furthermore, the main interaction between relatedness and presentation type was also significant (β = −1.532, SE = 0.753, Z = −2.033, p = 0.042). This main interaction suggests that the difference in the proportion of looking between related and unrelated targets was greater in the repeated than in the singular condition.

The exploration of the main interaction revealed that there were no significant differences between the related and unrelated conditions in either the repeated or the singular conditions (p > 0.314). Specifically, in the repeated condition, only the related trials showed a significant deviation from chance level ($t(31)$ = 4.239, p = 0.0001), while the unrelated trials did not ($t(31)$ = 0.483, p = 0.632). In contrast, the singular condition did not exhibit any significant differences (p > 0.38). These results suggest a priming effect on the repeated, but not in the singular presentation as early as 18 months.

The analysis of position contrast revealed a significant interaction between relatedness and the third position (β = −1.738, SE = 0.523, $t(36)$ = −3.322, p = 0.002). This interaction indicates that the prime produced more pronounced differences between related and unrelated trials when it was presented in the third position compared to the first position. Delving deeper into this main interaction, it was observed that toddlers directed their gaze more towards the related condition than the unrelated one when the prime appeared in the third position (β = 0.977, SE = 0.373, $t(18)$ = 2.623, p = 0.017). However, no significant differences between conditions were detected in either the first or second positions (p > 0.0528). When comparing against the chance level, neither the related nor the unrelated conditions in any position showed significant deviations (p > 0.064). In summary, the second contrast provided only modest evidence for the existence of priming effects with a single presentation of the prime words. Intriguingly, the direction of the priming effect shifts between the first and third presentations. However, this effect is absent when the prime is presented in the second position.

3.2. Growth curve analysis

The statistical values of the growth curve analysis for repeated vs. singular presentation are summarized in Table 1. The raw proportion of looking and the fitted model plots are presented in 5. For this first contrast, the main result of the growth curve analysis is the significant interaction among the three-time terms, the relatedness and the presentation type. In particular, the interaction among the linear terms, relatedness and presentation type (p = 0.004) indicates that repeated trials have a linear decrease over time which is faster in unrelated than related trials (5). By contrast, in the singular presentation, toddlers exhibit a linear increase in the target fixation in the unrelated trials but a decrease in the related ones (5).

The interaction between relatedness and presentation type with the quadratic term indicated sharper looking in an inverted U shape in the singular than in the repeated condition (p < 0.001). Thus, toddlers first looked more at the distractor and then at the target in the unrelated singular condition, but they had flat looking in the related singular condition.

Finally, the interaction between relatedness and presentation type with the cubic time term (p < 0.001) suggests that toddlers looked to the target, looked away, and finally returned to look at the target. This effect was mainly present for the repeated prime, and the looking peaks were higher in the related than the unrelated condition.

In sum, the growth curve analysis suggests that the presentation type changes the temporal dynamic of looking, and this effect is different in related and unrelated conditions.

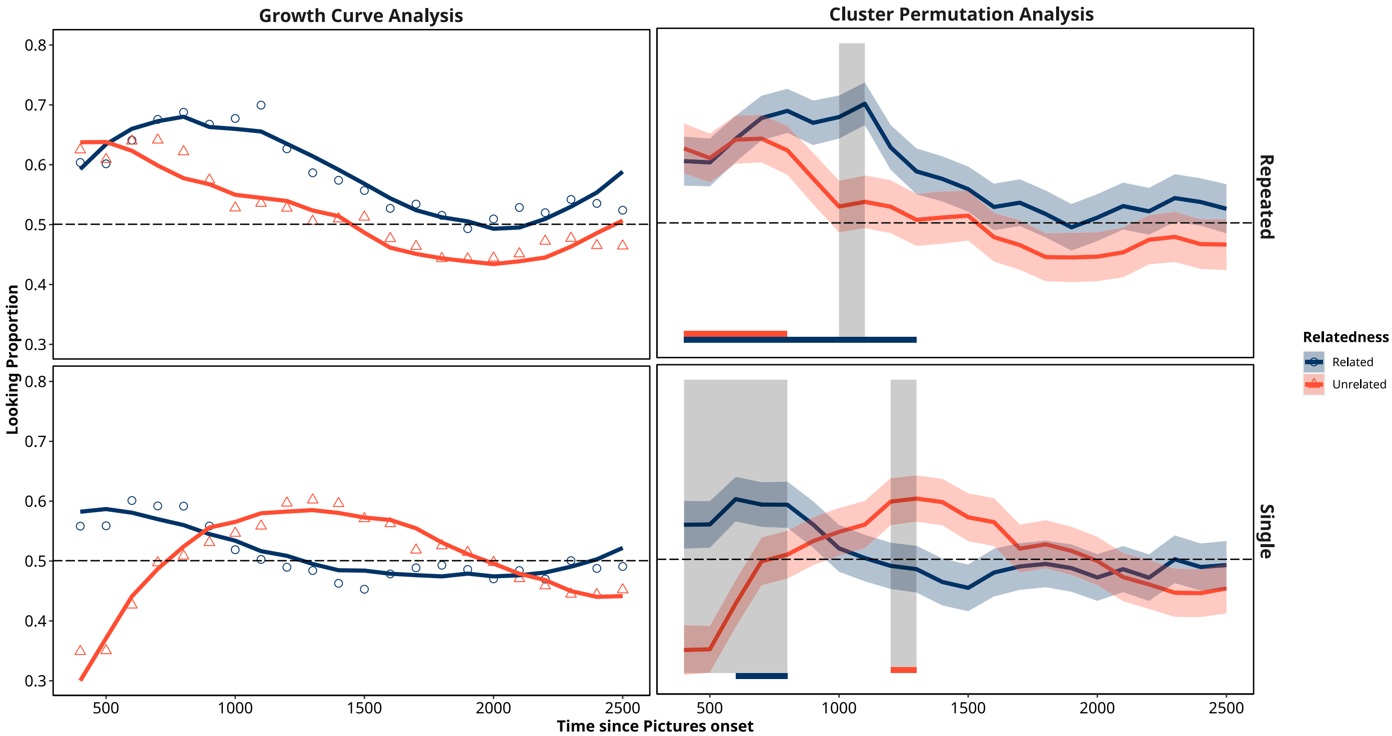

Fig. 5. Time course of presentation contrast. Note: Horizontal dashed lines indicate the chance level. **Left panels** show the raw time course with markers and the growth curve analysis with solid lines. **Right panels** show the means (solid lines) and standard errors (ribbons) of the raw time course of fixation. Grey shaded regions indicate significant clusters between conditions. Bottom lines show significant clusters against chance level for the related (blue) and unrelated (red) conditions.

Table 1
Growth curve analysis of Relatedness vs. Presentation contrast.

Fixed factor	β	SE	df	t	p
Intercept	0.096	0.145	12 582	0.661	0.508
Linear	**−0.897**	**0.291**	**12 582**	**−3.074**	**0.002**
Quadratic	0.710	0.396	12 582	1.791	0.073
Cubic	0.159	0.248	12 582	0.639	0.522
Relatedness	−0.176	0.207	646	−0.850	0.395
Presentation	**0.424**	**0.206**	**646**	**2.055**	**0.040**
Linear:Relatedness	**0.984**	**0.275**	**12 582**	**3.566**	**<0.001**
Quadratic:Relatedness	**−2.711**	**0.285**	**12 582**	**−9.492**	**<0.001**
Cubic:Relatedness	**0.734**	**0.284**	**12 582**	**2.578**	**0.009**
Linear:Presentation	−0.390	0.272	12 582	−1.433	0.151
Quadratic:Presentation	**−0.681**	**0.278**	**12 582**	**−2.444**	**0.014**
Cubic:Presentation	**0.890**	**0.280**	**12 582**	**3.173**	**0.001**
Relatedness:Presentation	**−0.288**	**0.295**	**646**	**−0.977**	0.328
Linear:Relatedness:Presentation	**−1.145**	**0.399**	**12 582**	**−2.865**	**0.004**
Quadratic:Relatedness:Presentation	**3.547**	**0.411**	**12 582**	**8.620**	**<0.001**
Cubic:Relatedness:Presentation	**−1.546**	**0.411**	**12 582**	**−3.759**	**<0.001**

Notes. Fixed factor: Relatedness (related, unrelated), Presentation (singular, repeated).
R function: log(Fixations/Non-fixations).
(Linear+Quadratic+Cubic) ∗ Relatedness ∗ Presentation+((Linear+Quadratic+Cubic)| Subject).
Analysis window: 367 to 2490 ms after the onset of the pictures.
Bold values indicate significant values.

Fig. 6 displays both the raw time course and the model pertaining to the position contrast. The statistical outcomes from the growth curve analysis for this contrast are detailed in Table 2. A significant interaction was observed between relatedness and position for both the linear ($p < 0.001$; see Fig. 6) and cubic ($p < 0.017$) terms when comparing the second and first positions. This finding implies that participants exhibited a more pronounced increase in their gaze towards the unrelated target over time compared to the related target. Conversely, when the prime was presented in the second position, there was a decline in the attention given to both related and unrelated trials, as illustrated in Fig. 6.

Additionally, there was an interaction between relatedness and position when comparing the third and first positions ($p = 0.048$). This indicates that toddlers were more inclined to look towards the related target when it was in the third position, whereas their attention was directed towards the unrelated target in the first position, as depicted in Fig. 6.

In sum, the growth curve analysis highlights the varying dynamics of the priming effect based on the presentation position of the prime word.

3.3. Cluster-based permutation analysis

5 shows the raw data plot and the significant clusters between condition and chance level comparisons. In the presentation type contrast (5), the cluster-based non-parametric analysis revealed more fixation to the target in related than unrelated trials in the repeated condition from 1000 to 1100 ms ($t_{cluster} = 4.156$, $t_{max} = 2.115$, $p_{cluster} = 0.003$). By contrast, in the singular condition (5), two clusters were present: an early cluster where toddlers looked more to the target in related than unrelated trials (400 to 800 ms; $t_{cluster} = 18.219$, $t_{max} = 5.080$, $p_{cluster} < 0.001$), and a late cluster with the inverse pattern, where participants looked more to the target in unrelated than the related trials (1200 to 1300 ms; $t_{cluster} = 4.296$, $t_{max} = 2.254$, $p_{cluster} = 0.024$).

Furthermore, toddlers' looking was greater than chance: in the repeated related condition from 400 to 1300 ms ($t_{cluster} = 44.51$, $t_{max} = 6.250$, $p_{cluster} < 0.001$); in the repeated unrelated condition from 400 to 800 ms ($t_{cluster} = 14.84$, tmax = 3.736, $p_{cluster} < 0.001$); in the singular related condition from 600 to 800 ms ($t_{cluster} = 8.447$, $t_{max} = 3.094$, $p_{cluster} < 0.001$); and in the singular unrelated condition from 1200 to 1300 ms ($t_{cluster} = 8.447$, $t_{max} = 3.094$, $p_{cluster} < 0.001$).

In sum, the repeated prime elicited an apparent facilitation effect, while the singular prime produced a mixed effect.

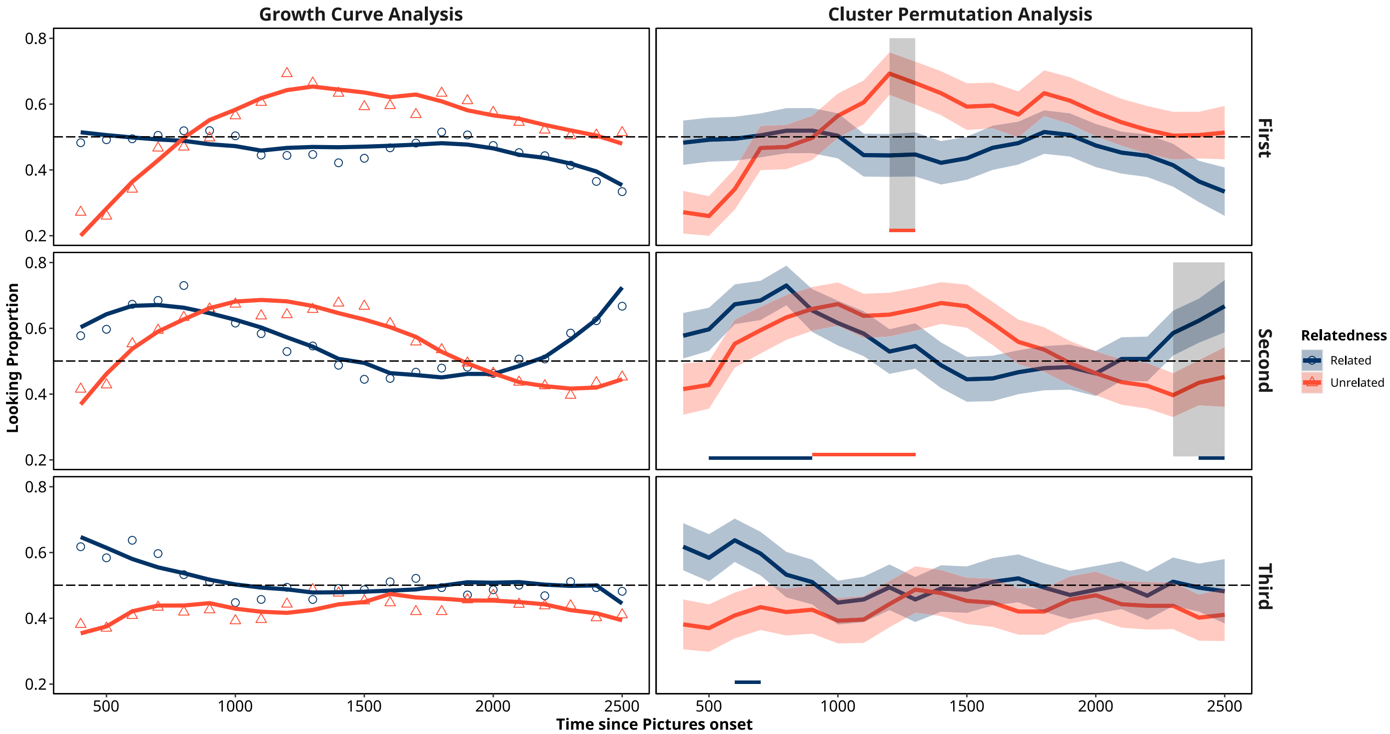

Fig. 6. Time course of position contrast. Note: Horizontal dashed lines indicate the chance level. **Left panels** show the raw time course with markers and the growth curve analysis with solid lines. **Right panels** show the means (solid lines) and standard errors (ribbons) of the raw time course of fixation. Grey shaded regions indicate significant clusters between conditions. Bottom lines show significant clusters against chance level for the related (blue) and unrelated (red) conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Growth curve analysis of Relatedness vs. Position contrast.

Fixed factor	β	SE	df	t	p
Intercept	−0.241	0.249	6327	−0.966	0.333
Linear	−0.867	0.524	6327	−1.654	0.098
Quadratic	0.184	0.586	6327	0.314	0.752
Cubic	−0.542	0.428	6327	−1.266	0.205
Relatedness	0.341	0.354	306	0.962	0.336
Second	**0.719**	**0.352**	**306**	**2.043**	**0.041**
Third	**0.301**	**0.363**	**306**	**0.828**	0.407
Linear:Relatedness	**2.389**	**0.504**	**6327**	**4.737**	**<0.001**
Quadratic:Relatedness	**−2.894**	**0.521**	**6327**	**−5.548**	**<0.001**
Cubic:Relatedness	**1.664**	**0.520**	**6327**	**3.197**	**0.001**
Linear:Second	−0.270	0.478	6327	−0.564	0.572
Linear:Third	−0.306	0.499	6327	−0.614	0.539
Quadratic:Second	**1.433**	**0.490**	**6327**	**2.922**	**0.003**
Quadratic:Third	0.974	0.517	6327	1.881	0.060
Cubic:Second	**2.147**	**0.494**	**6327**	**4.341**	**<0.001**
Cubic:Third	−0.001	0.513	6327	−0.003	0.996
Relatedness:Second	−0.524	0.503	306	−1.042	0.298
Relatedness:Third	**−1.022**	**0.516**	**306**	**−1.979**	**0.048**
Linear:Relatedness:Second	**−2.495**	**0.710**	**6327**	**−3.513**	**<0.001**
Linear:Relatedness:Third	−1.054	0.742	6327	−1.419	0.155
Quadratic:Relatedness:Second	−0.891	0.724	6327	−1.229	0.219
Quadratic:Relatedness:Third	1.050	0.770	6327	1.364	0.172
Cubic:Relatedness:Second	**−1.730**	**0.728**	**6327**	**−2.374**	**0.017**
Cubic:Relatedness:Third	−0.897	0.763	6327	−1.175	0.239

Notes. Fixed factor: Relatedness (related, unrelated), Position (first, second, third).
R function: log(Fixations/Non-fixations).
(Linear+Quadratic+Cubic) * Relatedness * Position+((Linear+Quadratic+Cubic)| Subject).
Analysis window: 367 to 2490 ms after the onset of the pictures.
Bold values indicate significant values.

Regarding the position comparisons, Fig. 6 shows the raw time course signal and the significant clusters. In this contrast, toddlers looked more to the target in the unrelated than the related condition when the prime was presented in the first position from 1200 to 1300 ms ($t_{cluster}$ = 4.883, t_{max} = 2.629, $p_{cluster}$ = 0.004). The opposite happened at the end of the trial (2300 to 2500 ms) in second position: participants looked more to the target in the related than the unrelated condition ($t_{cluster}$ = 8.030, t_{max} = 3.435, $p_{cluster}$ = 0.002). Furthermore, there were no systematic differences between conditions across time when the prime was presented in the third position.

In the chance comparisons, when the prime was presented in the first position (Fig. 6), toddlers did not look to the related target, but they looked above chance to the unrelated target from 1200 to 1300 ms ($t_{cluster}$ = 6.749, t_{max} = 3.548, $p_{cluster}$ = 0.0008). When the prime was presented in the second position (Fig. 6), participants looked above chance level in the related condition from 500 to 900 ms ($t_{cluster}$ = 14.092, t_{max} = 3.599, $p_{cluster}$ < 0.001), and from 2400 to 2500 ms ($t_{cluster}$ = 4.766, t_{max} = 2.662, $p_{cluster}$ = 0.024). They also looked above chance in the unrelated condition from 900 to 1300 ($t_{cluster}$ = 11.546, t_{max} = 2.608, $p_{cluster}$ < 0.001). Finally, when the prime was presented in the third position (Fig. 6), toddlers did not look at the unrelated target, but they did look at the related target above chance from 600 to 700 ms ($t_{cluster}$ = 5.579, t_{max} = 3.332, $p_{cluster}$ < 0.001).

In sum, the position of the prime modulated the type of priming effect: the target presented in the first position elicited a suppression effect on the target response in related trials, and the opposite pattern occurred in the third position.

4. Discussion

The experiment described in the current manuscript set out to answer two questions:

1. Does highlighting the saliency of the prime word in the inter-modal priming task through prime repetition enable a priming effect in 18-month-olds when no such effect was observed in the original priming study at this age (Arias-Trejo & Plunkett, 2009)?

2. When the prime is presented just once, does the timing (SOA) of the prime relative to the target word influence any observed priming effect?

The results of the experiment indicate that both questions can be answered in the affirmative: Repetition of the prime word leads to a general facilitation in the identification of related targets whereas singular presentations are ambiguous in their impact. Furthermore, the timing of singular primes determines the character of any priming effect observed.

We conducted 3 types of statistical analyses of the experimental data, including an overall proportional looking measure (as in the original Arias-Trejo & Plunkett, 2009 study), a growth curve analysis to examine any changes in looking patterns during the course of the trial, and a non-parametric cluster-based permutation analysis to identify any differences between experimental conditions and whether individual conditions differ from chance during the course of the trial. Each of these analyses provides a different perspective on the toddlers' patterns of looking behaviour in the experiment. We use these to better understand the effects of prime repetition and prime timing in turn.

4.1. Prime repetition

The overall proportion of looking measure shows that 18-month-old toddlers looked more at the target object during the Repeated presentation than the Singular presentation, and that the difference between the Related and Unrelated conditions was greater for Repeated presentation than Singular presentation (see Fig. 4). Furthermore, analysis of the difference between the Related and Unrelated conditions for Repeated presentation of the prime indicates a marginal effect of the prime which is completely absent in the Singular condition. The latter result constitutes a replication of Arias-Trejo and Plunkett's (2009) findings, whereas the former points to the existence of a weak priming effect when the prime is repeated. Thus, the overall proportion of looking measure suggests that our prediction that prime repetition facilitates priming is correct. In the absence of prime repetition, there is no evidence of priming using this overall proportional measure—the same measure used by Arias-Trejo and Plunkett (2009) who also found no evidence of priming with singular prime presentation at 18-months of age.

The non-parametric cluster-based permutation analysis of the target-looking behaviour in our 18-month-olds (5) reveals a more nuanced pattern of results. There is a brief (100 ms) but very robust priming effect observed for Repeated presentations such that Related primes produced greater looking at the target than Unrelated primes. Similarly, there is an early and extended (400 ms) priming effect for Singular presentations but this effect reverses later in the trial to produce the unexpected finding that Unrelated primes produce greater looking at the target than Related primes.

The growth curve analyses (GCA) (5 and Table 1) provide a picture of the unfolding preferences of looking throughout the trial. For Repeated presentations there is a continuous preference for the target in the Related condition from early on in the trial and throughout, as compared to the Unrelated condition, again supporting the existence of a priming effect for Repeated presentations. The GCA for Singular presentation reveals a completely different picture (in line with the cluster-based analysis): In the Related condition looking at the target generally decreases during the course of a trial after an early weak interest in the target. In the Unrelated condition, a strong early interest in the distractor is followed by a reversal to an interest in the target (again, in line with the cluster-based analysis). The GCA suggests that the early priming effect for Singular presentation in the cluster-based analyses is driven by the early preference for the distractor in the Unrelated condition rather than a strong preference for the target in the Related condition.

It is important to note that the stability and robustness of the priming effect in the repetition condition are indeed transient. This transient nature is anticipated, given that 18 months is the incipient age at which priming effects have been detected (Arias-Trejo, Angulo-Chavira, Avila-Varela, Chua-Rodriguez, & Mani, 2022; Delle Luche et al., 2014). Indeed, Arias-Trejo's (2022) preceding longitudinal studies, which investigated semantic priming with a singular prime presentation, have illustrated an amplification in both the magnitude and the persistence of the priming effect, progressing from 18 to 24 months of age.

At 18 months, the priming effect, albeit brief and fluctuating, manifests reliably. Then, as the child matures to 21 months, there is a notable prolongation in the duration of this effect. Eventually, by the age of 24 months, the semantic priming effect appears to solidify and stabilize. These developmental changes highlight the evolving nature of semantic processing capabilities in early childhood, pointing to a gradual strengthening and refinement of semantic networks and associations as toddlers grow

4.1.1. Summary

Overall, these analyses provide compelling evidence that repetition of the prime yields a robust and stable priming effect when using the inter-modal priming task with 18-month-olds. When the prime is presented just once, the evidence for priming is equivocal and unstable. We did not expect to see any priming effect with Singular presentation (replicating Arias-Trejo & Plunkett, 2009). This expectation was fulfilled when using the same measure as the original study. However, we did *not* predict a priming reversal as revealed by GCA and cluster-based analyses for Singular presentation. In particular, we did not predict that an Unrelated prime would elicit greater looking at the target than a Related prime in *any* experimental condition. As we shall see, the timing of the prime for Singular presentations sheds some light on this counter-intuitive result.

4.2. Prime timing

Singular prime presentations occurred at a stimulus onset asynchrony of 3200 ms, 2400 ms and 1000 ms in prime positions First, Second and Third, respectively. Given that the average duration of the prime was 700 ms, this yielded ISIs of approximately 2500 ms, 1700 ms and 300 ms in these positions. In all cases, prior to the onset of the target word, a coloured checkerboard was displayed on screen (see Fig. 2).

The overall proportional measure (Fig. 4) revealed that the timing of the prime had a substantial impact on target looking. When presented in First position, the unrelated prime yielded greater target looking than the related prime. When presented in Third position, the related prime yielded greater target looking than the unrelated prime. Second position yielded no prime effect. This pattern of effects points to a switch in the impact of the prime such that at long ISIs ($\approx$2500 ms) target looking is facilitated by an unrelated prime while at short ISIs ($\approx$300 ms) target looking is facilitated by a related prime. The intermediate ISI ($\approx$1700 ms) yielded no impact of prime relatedness on target looking, and suggested that infants failed to identify the target referent. Note that the failure to fixate the target referent systematically over the course of the trial when the prime is in the intermediate second position is surprising given that the target referent has been named just before the onset of the images (see Fig. 2). The fact that there is a switch in the priming effect from First position to Third position, also requires explanation. Note that the Third prime position corresponds closely to that used in the original Arias-Trejo and Plunkett (2009) study where no priming effect was found. The original study used a traditional ANOVA to analyse looking behaviour over the course of the trial, whereas the current study used a statistically more powerful binomial logistic mixed effects model. We suggest that the use of the statistically less powerful ANOVA may have been responsible for the failure to find any priming effect in the original study.

Fig. 6 presented the time course of fixations (calculated as the proportion of target looking in every 100 ms bin) and summarizes the results of the GCA and cluster-based permutation analyses for each of the 3 prime positions by condition (related vs. unrelated prime). The results for the First presentation position (≈2500 ms before target word onset) indicate that there is no evidence for systematic target identification at any point in the trial in the Related prime condition. In contrast, the Unrelated prime produces a rapidly changing shift away from the distractor object early in the trial to a clear preference for the target object later in the trial. The cluster analyses reveals a brief but significant priming effect about halfway through the trial. These analyses converge with the overall proportional measure in identifying a priming effect for First position presentations, though in the unexpected direction: Greater target looking is achieved for Unrelated primes as compared to Related primes.

The results for the Third presentation position (≈300 ms before target word onset) revealed no evidence whatsoever for a priming effect throughout the trial, though the cluster-based analyses revealed a brief but significant preference for the target object early in the trial for the Related prime. However, this target preference was not sufficient to support a priming effect. These analyses differ somewhat from those with the overall proportional measure which identified a priming effect for Related primes. The reason for this discrepancy is readily understood by examining Fig. 6: The GCA shows proportional looking at the target above or close to chance throughout the trial for the Related prime whereas target looking is consistently below chance throughout the trial for the Unrelated prime. When these differences are integrated across the whole trial (which is equivalent to the overall proportional measure), then a systematic priming effect emerges, i.e., a difference in target looking between the Related and Unrelated conditions.

The results for the Second presentation position (≈1700 ms before target word onset) present a more complex pattern of results not evident in the overall proportional measure. In the Related prime condition there is an early tendency to fixate the target object. This target preference then disappears for most of the trial only to reappear at the end. In contrast, in the Unrelated prime condition, a target preference emerges towards the middle of the trial only to disappear again at the end. Together, these shifting patterns of target preference for the Related and Unrelated conditions result in a brief but significant priming effect in the expected direction at the very end of the trial. It is clear that these shifting patterns of preference within each condition cancel each other out when analysed using the overall proportional measure.

4.2.1. Summary

Overall, the results show that the timing of the prime relative to target word onset has a profound effect on the preference for the target referent, all depending on the whether the prime is related or unrelated to the target. Perhaps the overall proportional analysis (Fig. 4) provides the simplest overview (though of course tempered by the more fine-scale GCA and cluster-based analyses): At very long ISIs (≈2500 ms), the Unrelated prime elicits a priming effect. At short ISIs (≈300 ms), the Related prime elicits a priming effect. In a medium ISI (≈1700 ms), there is no priming effect.

4.3. Mechanisms of priming

The findings of this study raise two theoretical questions:

1. How does the repetition of a prime facilitate a priming effect in 18-month-old toddlers when a singular presentation fails to do so?
2. What is the reason for the reversal in the effect of related and unrelated singular primes, such that a very long SOAs unrelated singular primes enhance target identification as compared to related singular primes whereas at short SOAs the standard priming effect is observed?

In order to answer (1), it is worth keeping in mind that, in the absence of a prime, toddlers readily identify a named referent in a standard IPL task, even when the target and distractor objects have labels with the same onset (e.g., Fernald, Swingley, & Pinto, 2001; Swingley, Pinto, & Fernald, 1999), as in the current experiment. Furthermore, we know from Arias-Trejo and Plunkett's (2009) study that a singular prime is sufficient to yield a priming effect at short ISIs for 21-month-olds. In these cross-modal priming studies, we suppose that related prime stimuli pre-activate the target word thereby facilitating target identification and fixation. Unrelated prime stimuli do not pre-activate the target word and so cannot facilitate identification and fixation in the same way. Any priming effect is indexed by enhanced looking at the target referent for the related prime compared to the unrelated prime.

Existing theories of semantic priming, in particular Spreading Activation Theories (Anderson, 1983; McNamara, 2005) and Distributed Representations models (Cree et al., 1999; McRae et al., 1997; Plaut & Booth, 2000; Rogers et al., 2004; Rogers & McClelland, 2004) explain how taxonomically and associatively related words prime each other: Distributed Representations models explain priming by semantic feature overlap. With high feature overlap, many features have been pre-activated and few features need to be changed when moving from one semantic representation to the other. Associatively related words pre-activate each other directly through associative links. Spreading Activation Theories explain priming by spreading of activations between taxonomically or associatively related words: the activation of a representation spreads to related representations pre-activating them.

Both Spreading Activation theories and Distributed Representations models can explain the impact of Inter Stimulus Interval (ISI) on semantic priming: We know that infant sensitivity to both taxonomic and associative relations is modulated by the ISI between words (Delle Luche et al., 2014; Plunkett et al., 2022): while taxonomic priming is a short lasting effect (⩽400 ms.), the injection of associative links between words makes the effect last longer (~800 ms.). This finding is consistent with the well-known *semantic or associative boost* effect reported for adults (Hutchison, 2003; Lucas, 2000; Moss, Hare, Day, & Tyler, 1994; Plaut & Booth, 2000).

For Spreading Activation theories the impact of ISI derives from the assumption that spreading of activation is a temporally bound phenomenon, such that activation *adapts* or *habituates* over time. On this approach, the activity derived from taxonomic priming is thought to habituate faster than that for associative priming. For Distributed Representation models, the asymmetry between taxonomic and associative priming is thought to derive from an *hysteresis* effect. According to Plaut and Booth (2000), the short-lived character of taxonomic priming is explained in terms of an hysteresis effect 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), non-overlapping features are not fully activated. Hence, overlapping features prime the transition to the target. At long SOAs (around 800 ms), non-overlapping 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, Bentin, & Shriki, 2012).

The repetition effects reported in the current paper are readily explained by either of the theoretical approaches outlined above. Both rely on pre-activation of the target word by the repeated prime stimuli: All related prime words are taxonomically related to the target word. Furthermore, the ISI between the repeated words was set at

500 ms so that priming can occur between the prime words themselves (repetition priming) and the target word (taxonomic priming). Hence, the representation of the target word is continuously *fed* activity from an increasingly active representation of the prime word during the course of a trial. It is not unreasonable to suppose that this continuous activation by the repeated prime yields an incrementally active target word representation which can then drive a more robust identification of the target referent, as compared to a repeated but unrelated prime which is associatively and taxonomically unrelated to the target word. Furthermore, if the semantic representations of the prime and target words are less robust in the 18-month-olds used in this study than the 21-month-olds used by Arias-Trejo and Plunkett (2009), then the priming effect is likely to benefit particularly from repeated presentations, mirroring stimulus degradation and frequency effects reported in the adult priming literature (Holcomb, 1993; Norris, 1984).

The second theoretical question (2) concerning the reversal in priming effects observed for related and unrelated primes in First position trials cannot be readily explained by the theoretical machinery offered by either of the standard accounts of semantic priming described above. Both Spreading Activation and Distributed Representation accounts predict an advantage or *no advantage* for related primes over unrelated primes, depending on the SOA. Of course, an advantage for related singular primes *is* observed at short SOAs in the current study (see Figs. 4 and 6). However, we suggest that further theoretical machinery is needed to explain why unrelated primes produce greater target looking than related primes at long SOAs (see Figs. 4 and 6). We propose that a form of *negative priming* (Neill, 1977; Tipper, 1985) is needed to explain this counter-intuitive result.

In a typical negative priming (NP) experiment, the participant must pay selective attention to a target stimulus and ignore a distractor stimulus during a prime phase of a trial. If the previously ignored stimulus is then used as the target in a subsequent probe phase of the trial, then response times to this ignored repetition are delayed as compared to a neutral probe trial where the target is unrelated to the target and distractor stimuli in the prime phase. Tipper (1985) attributed this NP effect to *spreading inhibition* of the ignored stimulus, such that subsequent attempts to identify it suffer interference. Tipper (1985) also argued that spreading inhibition affects perceptually and semantically related items. Thus, categorical or associative coordinates (e.g., dog and cat, or dog and bone) can negatively prime each other. NP is also considered to operate cross-modally (Driver & Baylis, 1993), to be long lasting and to take time (>1 s) to emerge (Fox, 1995; May, Kane, & Hasher, 1995). See Frings, Schneider, and Fox (2015) for a relatively recent review of the large literature on NP.

Evidence for NP effects during infancy is relatively sparse. Amso and Johnson (2005) have demonstrated spatial negative priming (SNP) effects in 9-month-old infants. At long ISIs between primes and probes, infants produced slower responses to previously ignored locations (ignored repetitions) than other control locations. SNP was not found with these infants using a short ISI (67 ms). NP has also been reported by Sučević and Plunkett (2021) with 18- and 26-month-olds. Their results revealed that both language-mediated and spatially-mediated priming led to attention-orienting during the probe phase: attended information during the prime phase facilitated attention during the probe phase while ignored features (both location and identity) were inhibited. However, in contrast to spatially-mediated attention during the prime phase, language-mediated attention was able override these inhibitory effects. The impact of language on overcoming inhibitory effects was particularly noteworthy in the older age group. Finally, backwards semantic inhibition (BSI) has been reported in 18–24-month-olds (Chow, Aimola Davies, Fuentes, & Plunkett, 2016, 2019): When switching attention from one semantic category to another, the former and no-longer-relevant semantic category becomes inhibited, and subsequent attention to an item that belongs to the inhibited semantic category is impaired. BSI in the 18-month-olds was only observed for those infants with larger vocabularies.

How is negative priming relevant to explaining the reverse priming effect observed for Singular Position One primes in the current experiment? i.e., where unrelated primes produce greater target looking than related primes. Of the 24 trials seen by each infant, only 4 of them are Position One trials with an ISI of ≈3100 ms between target and prime. Sixteen trials (including Position Three and repeated trials) have an ISI of ≈200 ms between prime and target and further 4 trials (Position Two trials) have an ISI of ≈1700 ms. During these ISIs, infants see a coloured checkerboard on screen which bears no relation to the linguistic stimuli they hear. We suggest that the unusually long interval between prime and target for Singular Position One trials is unexpected and that infants ignore this linguistic stimulus much as adults might ignore the unattended prime stimulus in a typical negative priming study. Furthermore, there is sufficient time lapsed prior to the onset of the target word (>3000 ms) for negative priming of the prime representation to emerge. Hence, the prime in Position One trials has the capacity to induce inhibition of related subsequent stimuli. For related Position One trials, NP will interfere with a response to the semantically related target. In contrast, no such interference will occur in unrelated Position One trials precisely because prime and target are unrelated. In this latter case, the unsupressed semantic representation of the target word is able to drive target identification and fixation of its own accord.

On this account, the reversal of the traditional priming effect is observed not because the unrelated prime pre-activates the target semantic representation but because the related prime inhibits it through negative priming. The target word in the unrelated condition can then drive referent identification as if there had been no prime stimulus. Indeed, the time course of target referent preference in First position trials produces a fairly typical overall preference in unrelated prime trials and no systematic target preference in the related prime trials (see Figs. 4 and 6), as seen in target word only IPL tasks (e.g., Fernald et al., 2001; Swingley & Aslin, 2000).

Other priming effects were also observed in the traditional direction for Second position and Third position trials (see Figs. 4 and 6). The latter was significant in the overall proportional measure but not for the cluster-based permutation analysis. The Second position priming effect was not observed in the overall proportional measure but was observed at the very end of the trial for the cluster-based permutation analysis. The clearest priming effect in the Singular condition was thus observed in the First position, and is consistent with a negative priming explanation.

Beyond our main hypothesis, there are other plausible explanations for the inhibitory effect in the first position and the facilitatory effect in the third position.

1. Decay of prime activation: As the duration between the prime and target stimuli increases, the activation of the prime stimulus in memory may start to decay (Anderson, 1983). This can lead to a reduction or reversal of the facilitation effect typically observed in semantic priming, causing interference instead.
2. Competition between related concepts: With a longer SOA, there is more time for related concepts in memory to become activated (Ratcliff & McKoon, 1988). These related concepts might compete with the target stimulus for attention and processing resources, leading to slower or more difficult target processing.
3. Inhibitory processes: Long SOAs might also trigger inhibitory processes that suppress the activation of the prime stimulus in memory (Neely, 1991; Neill, 1977; Tipper, 1985). This suppression can reduce the facilitation effect of the prime, causing interference when processing the target stimulus. This inhibitory effect can be particularly pronounced in tasks that involve the selection or discrimination of items from a set of alternatives, as the inhibition helps to reduce interference from irrelevant or distracting information.

Note that all these alternatives are not necessarily opposed to our main explanation; instead, they can work together.

4.4. Methodological contributions

In addition to its theoretical insights, this paper extends two significant methodological contributions to the study of lexical organization, with a specific focus on elucidating the emergence of lexical organization. Existing research has typically situated the onset of lexical organization between 18 and 24 months of age. However, our findings illustrate that the reinforcement of a prime word through repetition can indeed amplify the priming effect even in early infancy. This revelation furnishes a gateway to further investigate the evolution of lexical organization from a very early age, allowing for a more nuanced tracking of its inception and development.

Perhaps more significantly, our study facilitates exploration into the mechanisms underpinning lexical organization by varying the Stimulus Onset Asynchrony (SOA) between the prime and the target. Historically, manipulating the SOA has proven instrumental in distinguishing between automatic and strategic mechanisms in priming. Nevertheless, there is limited research with infants, with only one notable study by Styles and Plunkett (2009) addressing this variable. That study did not identify any significant differences between SOAs, but our work suggests that such conclusions might have been precipitous. A systematic manipulation of SOA is warranted to garner a more profound comprehension of the emergence and intricacies of human lexical organization.

5. Considerations

An important consideration in interpreting our findings is the relatively small number of trials for singular priming analysis, as they are divided into first, second, and third positions. While the observed effects were statistically significant, this division introduced a higher variability. As such, the limited statistical power warrants caution in generalizing the results. This is of particular significance as we observed certain effects that generally manifest early and transiently at the onset of the trial, only to reappear towards its conclusion (see Fig. 6, second position graph). Given that priming effects typically occur in the initial stages of word processing, we postulate that these subsequent appearances may represent noise, attributed to the variability inherent in both subjects and trials. Future studies with increased trial numbers would be beneficial to further validate and elucidate these findings.

In alignment with our planned analysis, we conducted a comparison between the repeated priming condition and the singular priming condition. Nonetheless, while our conclusions regarding the stability and robustness of priming in the repeated condition stand, the observed null effect in the singular condition – when all positions are aggregated – is not entirely accurate. This is due to the fact that the Stimulus Onset Asynchrony (SOA) between the prime and the target alters the direction of the effect, causing the longer and shorter positions to exhibit opposite effect directions, leading to a seemingly null overall effect. Indeed, it is accurate to state that the effect of the singular prime at each position is not only more variable but also weaker compared to the repeated one. Thus, the interactions between SOA, priming repetition, and effect directions are crucial for interpreting the nuanced behaviours observed in the singular priming condition

6. Conclusion

The primary goal of this study was to investigate whether semantic priming can be observed in 18-month-olds using the inter-modal priming technique. We aimed to enhance prime saliency through repetition and by adjusting the timing of the prime words. Our observations revealed that repeated exposure to a prime significantly influenced toddlers' attention towards both related and unrelated targets. This finding aligns with the spreading activation and distributed models of lexical organization. These models posit that word repetition reinforces the accessibility of related concepts within short-term memory, underscoring the interconnected nature of the lexicon. Our findings related to the timing of the singular prime showed unexpected patterns. Specifically, the interval between the prime and the target played a pivotal role in target identification. In certain scenarios, we noted a reversal of the priming effect, where unrelated primes led to greater target attention compared to related ones. We interpret this intriguing outcome in light of negative priming, suggesting a potential inhibitory mechanism in toddlers after a prolonged interval between stimuli. While this interpretation offers a novel perspective, it also calls for further empirical scrutiny. Beyond its theoretical insights, our study offers two pivotal methodological advancements. Firstly, we challenge the conventional timeline of the onset of lexical organization by demonstrating that reinforcing a prime word can amplify the priming effect even in early infancy. Secondly, we emphasize the significance of the interval between the prime and the target in understanding the mechanisms of lexical organization. In sum, our research has shed light on several mechanisms of the development of lexical access and organization during toddlerhood. It underscores the delicate balance between facilitatory and inhibitory effects in semantic priming and emphasizes the need for continued exploration.

Table A.1
List of the six target/distractor pairings together with the related and unrelated primes used either in the repeated or singular conditions. Each of the singular primes could be used in position one, two or three. No participant heard the same prime across trials more than once. Singular primes occurred just once in each position.
Source: Taken from University of South Florida adult free association norms (Nelson, McEvoy, & Schreiber, 2004).

Prime presentation	Relatedness	Prime	Target	Distractor
Single (2nd)	Related	Teddy	Balloon	Bowl
Repeated	Unrelated	Sock	Balloon	Bowl
Repeated	Related	Spoon[a]	Bowl	Balloon
Single (3rd)	Unrelated	Monkey	Bowl	Balloon
Repeated	Related	Fish	Bird	Biscuit
Repeated	Unrelated	Flower	Bird	Biscuit
Single (2nd)	Related	Milk	Biscuit	Bird
Single (2nd)	Unrelated	Cup	Biscuit	Bird
Single (1st)	Related	Pig	Horse	Hand
Repeated	Unrelated	Bath	Horse	Hand
Repeated	Related	Foot[a]	Hand	Horse
Single (2nd)	Unrelated	Bottle	Hand	Horse
Repeated	Related	Lion	Sheep	Shoe
Repeated	Unrelated	Train	Sheep	Shoe
Single (3rd)	Related	Hat	Shoe	Sheep
Single (1st)	Unrelated	Ball	Shoe	Sheep
Single (1st)	Related	Chair	Door	Dog
Single (1st)	Unrelated	Nappy	Door	Dog
Repeated	Related	Cat[a]	Dog	Door
Repeated	Unrelated	Boat	Dog	Door
Repeated	Related	Bus[a]	Car	Cow
Single (3rd)	Unrelated	Table	Car	Cow
Single (3rd)	Related	Duck	Cow	Car
Repeated	Unrelated	Apple	Cow	Car

[a] Indicates primes which were also associatively related to the target.

CRediT authorship contribution statement

Nicola Gillen: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Armando Quetzalcóatl Angulo-Chavira:** Software, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Kim Plunkett:** Conceptualization, Methodology, Investigation, Resources, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and analysis code are available at: https://osf.io/ap4ch/?view_only=061a460c232d47249e1b01e4f6531311.

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Appendix

See Table A.1.

References

Amso, D., & Johnson, S. P. (2005). Selection and inhibition in infancy: Evidence from the spatial negative priming paradigm. *Cognition*, *95*(2), B27–B36.

Anderson, J. R. (1983). A spreading activation theory of memory. *Journal of Verbal Learning and Verbal Behavior*, *22*, 261–295.

Angulo-Chavira, Armando Quetzalcóatl, & Arias-Trejo, Natalia (2021). Mediated semantic priming interference in toddlers as seen through pupil dynamics. *Journal of Experimental Child Psychology*, [ISSN: 0022-0965] *208*, Article 105146. http://dx.doi.org/10.1016/j.jecp.2021.105146.

Arias-Trejo, Natalia, Angulo-Chavira, Armando Q, Avila-Varela, Daniela S, Chua-Rodriguez, Fernanda, & Mani, Nivedita (2022). Developmental changes in phonological and semantic priming effects in spanish-speaking toddlers. *Developmental psychology*, *58*(2), 236–251. http://dx.doi.org/10.1037/dev0001290.

Arias-Trejo, N., & Plunkett, K. (2009). Lexical-semantic priming effects in infancy.. *Philosophical Transactions of the Royal Society B*, *364*, 3633–3647.

Arias-Trejo, Natalia, & Plunkett, Kim (2013). What's in a link: associative and taxonomic priming effects in the infant lexicon. *Cognition*, *128*(2), 214–227.

Barr, D. J. (2008). Analyzing 'visual world' eyetracking data using multilevel logistic regression. *Journal of Memory and Language*, *59*, 457–474.

Beckage, N., Smith, L., & Hills, T. (2011). Small worlds and semantic network growth in typical and late talkers. *PLoS One*, *6*(5), Article e19348.

Brainard, David H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436.

Chow, J., Aimola Davies, A. M., Fuentes, L. J., & Plunkett, K. (2016). Backward semantic inhibition in toddlers. *Psychological Science*, *27*(10), 1312–1320.

Chow, Janette, Aimola Davies, Anne M, Fuentes, Luis J, & Plunkett, Kim (2019). The vocabulary spurt predicts the emergence of backward semantic inhibition in 18-month-old toddlers. *Developmental Science*, *22*(2), Article e12754.

Chow, Janette, Angulo-Chavira, Armando Q, Spangenberg, Marlene, Hentrup, Leonie, & Plunkett, Kim (2022). Bottom-up processes dominate early word recognition in toddlers. *Cognition*, *228*, Article 105214.

Chow, Janette, Davies, Anne Aimola, & Plunkett, Kim (2017). Spoken-word recognition in 2-year-olds: the tug of war between phonological and semantic activation. *Journal of Memory and Language*, *93*, 104–134. http://dx.doi.org/10.1016/j.jml.2016.08.004.

Cree, G. S., McRae, K., & McNorgan, C. (1999). An attractor model of lexical conceptual processing: Simulating semantic priming. *Cognitive Science*, *23*, 371–414.

Delle Luche, C., Durrant, S., Floccia, C., & Plunkett, K. (2014). Implicit meaning in 18-month-old toddlers. *Dev Sci*, *17*(6), 948–955.

Dink, J., & Ferguson, B. (2018). Eyetrackingr. R package version 0.1.8.

Driver, J., & Baylis, G. C. (1993). Cross-modal negative priming and interference in selective attention. *Bulletin of the Psychonomic Society*, *31*(1), 45–48.

Fernald, A., Swingley, D., & Pinto, J. P. (2001). When half a word is enough: Infants can recognize spoken words using partial phonetic information. *Child Development*, *72*(4), 1003–1015.

Fitzpatrick, N. (2023). *What relationships exist between words in the lexical-semantc systems of toddlers* (Ph.D. thesis), UK: School of Psychology, University of Plymouth.

Floccia, Caroline, Delle Luche, Claire, Lepadatu, Irina, Chow, Janette, Ratnage, Paul, & Plunkett, Kim (2020). Translation equivalent and cross-language semantic priming in bilingual toddlers. *Journal of Memory and Language*, *112*, Article 104086.

Fox, E. (1995). Negative priming from ignored distractors in visual selection: A review. *Psychonomic Bulletin & Review*, *2*, 145–173.

Frings, C., Schneider, K. K., & Fox, E. (2015). The negative priming paradigm: An update and implications for selective attention. *Psychonomic Bulletin & Review*, *22*, 1577–1597.

Hamilton, Antonia, Plunkett, Kim, & Schafer, Graham (2000). Infant vocabulary development assessed with a british communicative development inventory. *Journal of child language*, *27*(3), 689–705. http://dx.doi.org/10.1017/S0305000900004414.

Hills, T. T., Maouene, M., Maouene, J., Sheya, A., & Smith, L. (2009). Categorical structure among shared features in networks of early-learned nouns. *Cognition*, *112*(3), 381–396.

Hills, T. T., Maouene, J., Riordan, B., & Smith, L. B. (2010). The associative structure of language: Contextual diversity in early word learning. *Journal of Memory and Language*, *63*(3), 259–273.

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the n400 in language processing. *Psychophysiology*, *30*(1), 47–61.

Huang, Y., & Snedeker, J. (2020). Evidence from the visual world paradigm raises questions about unaccusativity and growth curve analyses. *Cognition*, *200*, Article 104251.

Huber, D. E., & O'Reilly, R. C. (2003). Persistence and accommodation in short-term priming and other perceptual paradigms: temporal segregation through synaptic depression. *Cognitive Science*, *27*, 403–430.

Hutchison, K. a. (2003). Is semantic priming due to association strength or feature overlap? A microanalytic review. *Psychonomic Bulletin & Review*, *10*(4), 785–813.

Joordens, S., & Besner, D. (1992). Priming effects that span an intervening unrelated word: Implications for models of memory representation and retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(3), 483.

Kalénine, S., Peyrin, C., Pichat, C., Segebarth, C., Bonthoux, F., & Baciu, M. (2009). The sensory-motor specificity of taxonomic and thematic conceptual relations: A behavioral and fmri study. *Neuroimage*, *44*(3), 1152–1162.

Kleiner, Mario, Brainard, David, & Pelli, Denis (2007). What's new in Psychtoolbox-3?. *Perception*, *36*.

Lerner, I., Bentin, S., & Shriki, O. (2012). Spreading activation in an attractor network with latching dynamics: Automatic semantic priming revisited. *Cognitive Science*, *36*(8), 1339–1382.

Lucas, M. (2000). Semantic priming without association: A meta-analytic review. *Psychonomic Bulletin & Review*, *7*(4), 618–630.

Mani, Nivedita, & Plunkett, Kim (2007). Phonological specificity of vowels and consonants in early lexical representations. *Journal of Memory and Language*, *57*(2), 252–272.

Mani, Nivedita, & Plunkett, Kim (2010). In the infant's mind's ear: evidence for implicit naming in 18-month-olds. *Psychological Science*, *21*(7), 908–913.

Mani, Nivedita, & Plunkett, Kim (2011). Phonological priming and cohort effects in toddlers. *Cognition*, *121*(2), 196–206.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of eeg- and meg-data. *Journal of Neuroscience Methods*, *164*, 177–190.

May, C. P., Kane, M. J., & Hasher, L. (1995). Determinants of negative priming. *Psychological Bulletin*, *118*(1), 35.

McMurray, B. (2007). Defusing the childhood vocabulary explosion. *Science*, *317*(5838), 631–631.

McNamara, T. P. (2005). *Semantic priming: perspectives from memory and word recognition*. New York: Psychology Press.

McRae, K., de Sa, V. R., & Seidenberg, M. S. (1997). On the nature and scope of featural representations of word meaning. *Experimental Psychology: General*, *126*(2), 99–130.

McShane, J. (1979). The development of naming. *Linguistics*, *17*, 879–905.

Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of Experimental Psychology*, *90*(2), 227.

Mirman, D. (2014). *Growth curve analysis and visualization using R*. Taylor Francis Group: CRC Press.

Mirman, D., Dixon, J. A., & Magnuson, J. S. (2008). Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *Journal of Memory and Language*, *59*(4), 475–494.

Mirman, D., & Graziano, K. M. (2012). Individual differences in the strength of taxonomic versus thematic relations. *Journal of Experimental Psychology: General*, *141*(4), 601.

Mirman, D., Landrigan, J., & Britt, A. (2017). Taxonomic and thematic semantic systems. *Psychological Bulletin*, *143*(5), 499–520.

Moss, H., Hare, M., Day, P., & Tyler, L. K. (1994). A distributed memory model of the associative boost in semantic priming. *Connection Science*, *6*(4), 413–427.

Moss, H. E., Ostrin, R. K., Tyler, L. K., & Marslen-Wilson, W. D. (1995). Accessing different types of lexical semantic information: Evidence from priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(4), 863.

Murphy, K., & Hunt, H. (2013). The time course of semantic and associative priming effects is different in an attentional blink task. *Cognitive Processing*, *14*, 283–292.

Neely, J. H. (1991). Semantic priming effects in visual word recognition: a selective review of current findings and theories. In D. Besner, & G. W. Humphreys (Eds.), *Basic processes in reading: visual word recognition* (pp. 264–336). Hillsdale, NJ: Erlbaum.

Neill, W. T. (1977). Inhibitory and facilitatory processes in selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(3), 444.

Neill, W. T. (1997). Episodic retrieval in negative priming and repetition priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*(6), 1291–1305.

Nelson, D. L., McEvoy, C. L., & Schreiber, T. A. (2004). The university of south florida free association, rhyme, and word fragment norms. *Behavior Research Methods, Instruments, & Computers*, *36*(3), 402–407.

Norris, D. (1984). The effects of frequency, repetition and stimulus quality in visual word recognition. *The Quarterly Journal of Experimental Psychology*, *36*(3), 507–518.

Pelli, Denis G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial vision*, *10*, 437–442.
Plaut, D. C. (1995). Semantic and associative priming in a distributed attractor network. In *Proceedings of the 17th annual conference of the cognitive science society, Volume 17* (pp. 37–42). Pittsburgh, PA.
Plaut, D. C., & Booth, J. R. (2000). Individual and developmental differences in semantic priming: Empirical and computational support for a single-mechanism account of lexical processing. *Psychological Review*, *107*, 786–823.
Plunkett, Kim (1993). Lexical segmentation and vocabulary growth in early language acquisition. *Journal of Child Language*, *20*(1), 43–60.
Plunkett, K., Delle Luche, C., Hills, T., & Floccia, C. (2022). Tracking the associative boost in infancy. *Infancy*, 1–18. http://dx.doi.org/10.1111/infa.12502.
Posner, M. I., & Snyder, C. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition: the loyola symposium* (pp. 55–85). Hillsdale, NJ: Erlbaum.
Ratcliff, R., & McKoon, G. (1988). A retrieval theory of priming in memory. *Psychological Review*, *95*(3), 385–408.
Rogers, T. T., Lambo. Ralph, M. A., Garrard, P., Bozeat, S., McClelland, J. L., Hodges, J. R., et al. (2004). Structure and deterioration of semantic memory: A neuropsychological and computational investigation. *Psychological Review*, *111*, 205–235.
Rogers, T. T., & McClelland, J. L. (2004). *Semantic cognition: a parallel distributed processing approach*. Cambridge, MA: MIT Press.
RStudio Team (2020). *RStudio: integrated development environment for R*. Boston, MA: RStudio, PBC.
Schwartz, M. F., Kimberg, D. Y., Walker, G. M., Brecher, A., Faseyitan, O. K., Dell, G. S., et al. (2011). Neuroanatomical dissociation for taxonomic and thematic knowledge in the human brain. *Proceedings of the National Academy of Sciences*, *108*(20), 8520–8524.
Seidenberg, M. S., Waters, G. S., Sanders, M., & Langer, P. (1984). Pre-and postlexical loci of contextual effects on word recognition. *Memory & Cognition*, *12*(4), 315–328.
Shelton, J. R., & Martin, R. C. (1992). How semantic is automatic semantic priming? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(6), 1191.
Styles, S., & Plunkett, K. (2009). How do infants build a semantic system?. *Language and Cognition*, *1*, 1–24.
Sučević, Jelena, & Plunkett, Kim (2021). Language-and spatially-mediated attention in toddlers. *43*, In *Proceedings of the Annual Meeting of the Cognitive Science Society*.
Swingley, D., & Aslin, R. N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition*, *76*(2), 147–166.
Swingley, D., Pinto, J. P., & Fernald, A. (1998). Assessing the speed and accuracy of word recognition in infants. *Advances in Infancy Research*, *12*, 257–277.
Swingley, D., Pinto, J. P., & Fernald, A. (1999). Continuous processing in word recognition at 24 months. *Cognition*, *71*, 73–108.
Tipper, S. P. (1985). The negative priming effect: inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology*, *37A*(4), 571–590.
Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science*, *247*(4940), 301–306.
Willits, J. A., Wojcik, E. H., Seidenberg, M. S., & Saffran, J. R. (2013). Toddlers activate lexical semantic knowledge in the absence of visual referents: Evidence from auditory priming. *Infancy*, *18*(6), 1053–1075.