A longitudinal study of the role of vocabulary size on priming effects in early childhood

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Abstract

Studies on lexical development in young children have routinely suggested that the organisation of the early lexicon may change with age and increasing vocabulary size. In the current study, we explicitly examine this suggestion in further detail using a longitudinal study of the development of phonological and semantic priming effects in the same group of toddlers at three different ages. In particular, we examine the extent to which the development of these effects is influenced by the increasing vocabulary size of the child, since our longitudinal design allows us to disentangle the effects of increasing age and vocabulary size. We tested phonological and semantic priming effects in monolingual German infants at 18-, 21- and 24-months-old. We used the intermodal preferential looking paradigm combined with eye tracking to measure the influence of phonologically and semantic related/unrelated primes on target recognition. In addition, Growth Curve Analysis examined the trajectory of infants' looking behaviour during target recognition. Even after controlling for age at test, both phonological and semantic priming effects were influenced by participants' receptive and expressive vocabulary size respectively. In particular, children with larger receptive vocabularies showed phonological interference effects, while children with smaller receptive vocabularies showed phonological facilitation effects. With regards to semantic priming, we found an overall semantic interference effect, which was modulated by expressive vocabulary size. These results highlight the fact that vocabulary size is a strong predictor of the development of phonological and semantic priming effects in early childhood, even after controlling for age.

Keywords: infant, eye-tracking, longitudinal study, vocabulary, word recognition.

1. Introduction

Language comprehension begins early in life. For instance, evidence suggests that 3- to 6-month-old infants reliably learn word-object pairings that they have been briefly familiarized with in the lab (Friedrich & Friederici, 2011, 2015; Shukla, White, & Aslin, 2011). By around 6-months of age, infants show comprehension of the first words learned in their natural environment (Bergelson & Aslin, 2017a; Bergelson & Swingley, 2012). Parental reports further indicate that a first acceleration in vocabulary growth is seen around 16- to 20-months of life followed by a second burst from 24- to 30-months of age (Bates & Goldman, 1997; Fenson et. al, 1994). Importantly, however, despite children´s notable proficiency in building, storing and using words properly, these are not trivial tasks. To succeed in it, infants must simultaneously coordinate multiple cognitive skills (phonological discrimination, visual perception, motor control, processing memory, among others).

Importantly, this rapid expansion in vocabulary might further necessitate that children learn to detect similarities among words in their vocabulary and organise their lexicons along repeatedly reoccurring dimensions to better store the words they acquire. Indeed, there are an increasing number of studies suggesting that children are able to detect the similarities in the phonological (Mani & Plunkett, 2010, 2011) and semantic properties associated with the words (Arias-Trejo & Plunkett, 2009, 2013; Mani, Durrant & Floccia, 2012; Altvater-Mackensen & Mani, 2013), and visuo-perceptual properties of their referents (Arias-Trejo & Plunkett, 2010; Johnson, McQueen & Huettig, 2011; Mani, Johnson, McQueen & Huettig, 2013; Bobb, Huettig & Mani, 2016). These studies have typically been taken to suggest that words are organised according to their phonological, semantic and visuo-perceptual properties in the mental lexicon (see Mani & Borovsky, 2017 for a review).

Against this background, the current study examines the development of phonological and semantic links between words in the early lexicon. We focus on this crucial period of vocabulary expansion in the second year of life, namely, from 18- to 24-months of age, with particular attention to the role of individual children's vocabulary sizes on the formation of such links. In what follows next, we will first describe the paradigms typically used to examine such phenomena in young children, followed by a review of studies examining the phonological and semantic organisation of words in the early lexicon.

Classically, studies examining the organisation of words in the early lexicon have used a priming adaptation of the intermodal preferential looking paradigm (IPL). In the original IPL paradigm (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987), two pictures are presented side-by-side on-screen (e.g., an *apple* and a *table*), while an audio recording names one of the displayed objects, (e.g., Oh! Look at the *apple*!). In the priming adaptation of this task, the images and the target labels are preceded by a prime stimulus, which could be either a label (e.g., Styles, Arias-Trejo, & Plunkett, 2008) or an image that overlaps in certain features with the target (e.g., Mani & Plunkett, 2010). Typically, the prior presentation of a related prime leads to either improvement or delay in target recognition (relative to an unrelated prime) depending on the type of the relationship between the prime and the target: Facilitation effects on word recognition are typically indexed by shorter response times to fixate the target or increased fixations to the target when the target label is preceded by a related prime relative to an unrelated prime. Interference effects on word recognition are either indexed by longer response times to fixate the target or reduced fixations to the target when the target label is preceded by a related prime relative to an unrelated prime. Recently, this priming adaptation has been combined with automated eye tracking (see Delle-Luche, Durrant, Poltrock, & Floccia, 2015; Golinkoff, Ma, Song, & Hirsh-Pasek, 2013, for methodological reviews) and event-related potential methodologies (e.g., Rämä, Sirri, & Goyet, 2018; Rämä, Sirri, & Serres, 2013; Torkildsen, Syversen, Moen, Simonsen, & Lindgren, 2007).

Importantly, studies to date on priming effects in early word recognition are typically cross-sectional. Therefore, the results of when such priming effects begin to appear in development and their interaction with children's vocabulary size may merely reflect the cohort of participants studied at each unique point in time. In contrast, in order to attain a picture of developmental changes on priming effects in infancy, we applied a longitudinal design. We aim with this work to provide a longitudinal view of the development of phonological and semantic lexical links in monolingual infants and to clarify the role of participants' vocabulary size in the development of such links between words in the early lexicon. Not only will such a longitudinal design allow us to better pinpoint the role of infants' vocabulary size on the development of phonological and semantic links between words, the simultaneous comparison of phonological and semantic priming effects on the same cohort of children across this period of development, will allow us to examine how the development of phonological and semantic links mutually influence one another. This will be of key importance to previous studies and models of lexical organisation (Huettig & McQueen, 2007; Chow, Aimola Davies & Plunkett, 2017; Gaskell & Marslen-Wilson, 2002), highlighting how the semantic and phonological properties of words interact during the development of lexical links between words to support word recognition.

1.1. Phonological priming effects in early childhood

The study of phonological links in the early lexicon is typically undertaken by presenting infants with words, which overlap in some phonological features, and examining the time course and pattern of their recognition of the related words. These studies show, for instance, that 18-month-olds recognize a target better (e.g., *dog*) when it is preceded by a phonologically related prime (e.g., *door*) compared to an unrelated word (e.g., *boat*, Mani & Plunkett, 2010). However, this initial facilitation effect morphs into an interference effect at 24-months of age (Mani & Plunkett, 2011), such that two-year-olds look longer to the target (e.g., *dog*), when it is preceded by an unrelated word (e.g., *boat*) compared to a related word (e.g., *door*). This shift has been attributed to the increasing number of phonologically similar sounding words known by older children. This suggestion is supported by the finding that phonological interference effects are mediated by the cohort size of prime and target words

(Mani & Plunkett, 2008, 2011) used. The authors explain this result by suggesting, as proposed in some models of word recognition (Marslen-Wilson & Welsh, 1978; Gaskell & Marlsen-Wilson, 2002), that other similar sounding words are retrieved during word recognition. When the number of alternative phonological overlapping candidates exceeds a critical mass, their activation interferes with target recognition. They further explain the contrast between the findings at 18- and 24-months of age with a switch from phonologically to lexically driven effects with increasing vocabulary size (Mani & Borovsky, 2017). Early in life, with fewer words in the lexicon, hearing similar words may not trigger similar inhibitory lexical level effects and recognition may be eased by the phonological overlap between words. The larger vocabularies later in development may lead to greater competition between words and the introduction of inhibitory links between words in more mature lexicons (see also Mayor & Plunkett, 2014).

Indeed, a similar pattern of results is reported by Swingley, Pinto, & Fernald (1999) with 24-month-olds and adults. In this case, they manipulated the phonological overlap between the labels of target and distractor images (onset-overlap, e.g., *tree-track*, rhyme-overlap, e.g., *duck-truck* or unrelated, e.g., *ball-duck*). They found that the toddlers were slower to recognize the target when a competing distractor with a similar onset was presented, but not when target and distractor rhymed or shared no phonological overlap. Note, however that Altvater-Mackensen and Mani (2015) report a phonological priming effect when the prime and target rhymed but differed on the initial consonant, for example as in the German pair *Fisch-Tisch* (Engl. "fish-table"), suggesting that toddler's word recognition may also be affected by the phonological similarities on the rhyme of the words (see also Altvater-Mackensen & Mani, 2013).

The phonological priming paradigm has also been applied with children with hearing loss (Jerger, Tye-Murray, Damian, & Abdi, 2016) and Downs syndrome (Ramos-Sanchez & Arias-Trejo, 2018), highlighting the pervasiveness of this finding. In addition, this phonological priming paradigm has been applied with bilingual children and adults using eyetracking (Von Holzen & Mani, 2012; Von Holzen, Fenell, & Mani, 2018) and ERP methodologies (Von Holzen & Mani, 2014), showing that phonological priming effects also occur across languages in bilingual toddlers.

Continuing with the investigation of the neurological underpinnings of the phonological priming effects, Becker, Schild and Friedrich (2014) presented 6-, 12-, 18- and 24-month-olds pairs of an isolated syllable (prime) followed by a disyllabic spoken word (target), which were either congruent (e.g., *ma-Mama*, Engl. mommy) or incongruent with that prime (e.g., *so-Mama*). The authors found that even 6-month-olds appear to use the prime to ease processing of the subsequent phonologically similar target. However, only 24-month-olds showed suggestions of a left-lateralized P350-like deflection, which is an event-related potential related to word recognition in adults. Becker, Schild and Friedrich (2017) extended this with younger infants (3-month-olds) to suggest that infant speech processing shifts from a prosodic focus to a phonemic focus at 6-months of age, with early word recognition being primed by prosodic overlap and later recognition primed by phonological overlap (see also, Teickner, Becker, Schild & Friedrich, 2018).

Taken together, the reviewed literature highlights a developmental trend where experience with language plays an important role in the development of phonological links between words, with one potential sensitive period between 3- to 6-months of age, and a further period between 18- and 24-months of age (Mani & Borovsky, 2017; Mayor & Plunkett, 2014). Against this background and given our focus on the formation of *lexical* links between early words, we examine the development of phonological links between words during this latter period of 18- to 24-months of age.

1.2. Semantic priming effects in early childhood

The study of the semantic organization in the early lexicon is typically undertaken by presenting children with words related in meaning and examining the recognition of a given word when it was preceded by a semantically related prime compared to an unrelated prime. Studies adapting the IPL paradigm with semantic priming initially examined the formation of taxonomically and associative links between words in the early lexicon. Taxonomic semantic links refer to words that are exemplars of the same supra-ordinate category, e.g., the words *dog* and *chicken* which form part of the category *animal*. In contrast, associative links describe pairs of words that frequently co-occur in language use (e.g., *dog-bone*). Combining the two, the pair e.g., *dog-cat*, highlight a combined taxonomic and associative link between words.

Based on this distinction, research suggests that at 18-months infants do not display sensitivity to either associative or taxonomic links between words (Arias-Trejo & Plunkett, 2009; see also Styles & Plunkett, 2009, 2011). Later on, at 21-months of life, infants demonstrate a semantic priming effect, looking longer to a target when it was preceded by the presentation of a taxonomically *and* associatively related prime (Arias-Trejo & Plunkett, 2009). Then, only at 24-months of age do toddlers show sensitivity to not only combined associative and taxonomic links (Styles & Plunkett, 2009, 2011), but also to purely associative or purely taxonomically links between words (Arias-Trejo & Plunkett, 2013).

Some recent studies applying simplified versions of the experimental design in word recognition tasks, however, report earlier semantic priming effects. For instance, Bergelson and Aslin, (2017b) presented 12- to 14-month-old infants with pairs of pictures (e.g., *foot* and *juice*) as they named a matching word (e.g., *foot*) or an absent but semantically related word (e.g., *sock*). Here, while younger children fixated the target, i.e., foot, equally in matching and semantically related conditions, older children fixated the referent more in the matching condition relative to the semantically related condition. The authors interpret these findings as highlighting the fine-tuning of early semantic representations during the second year of life. Similarly, applying other methodologies such as the Head Turn Preference Procedure (HPP), studies report earlier semantic priming effects in 18-month-olds (Delle Luche, Durrant, Floccia & Plunkett, 2014) and semantic priming effects at 24-month-olds (Willits, Wojcik, Seidenberg & Saffran, 2013). These studies typically present children with lists of related (e.g., *dog, cat, cow, pig*) or unrelated words, and examine differences in listening times to the former relative to the latter as an index of sensitivity to the semantic relatedness of words. The authors explain the difference in results between the IPL studies and the Head Turn Preference studies with recourse to the paradigm used: the IPL paradigm, e.g., in Arias-Trejo and Plunkett (2013) requires to infants to simultaneously process visual and auditory information entailing a higher cognitive load relative to the HPP method (Delle Luche et al., 2014).

As with phonological priming effects, the pervasiveness of semantic priming effects is underscored by similar findings in bilingual toddlers (Singh, 2014) and there is also extensive investigation of the neurological underpinnings of these effects. ERP studies typically concentrate on a negative going potential, the N400, which peaks around 350ms and 550ms post-target onset and is typically more negative for unrelated than for semantically related prime-target word pairs (Kutas & Hillyard, 1980). A negative potential in a similar time window has been studied in infants to investigate the influence of the semantic memory structure on language processing (Mills, Coffey-Corina & Neville, 1997; Mills et al, 2004). In Mills et al. (1997), the authors report that 13- to 20-month-old infants show larger N200 and N375 potentials to familiar words than for novel or backward words, indicating that these components reflect word recognition. In addition, an N400-like response has been found in incongruous picture-word matching studies (e.g., naming *dog*, while displaying the image of a *car*) highlighting infants' sensitivity to the semantic match between a label and a referent picture (Friedrich & Friederici, 2004, 2006; Torkildsen et al., 2006). Importantly, in their study, Torkildsen et al. (2006) manipulated the type of incongruity presented to 20-month-olds infants, ranging from either within-category (e.g., naming a *cat* displaying the picture of a *dog*) or between-category mismatch (e.g., naming a *car* displaying the picture of a *dog*).

Although they report an N400-like effect for both conditions, this was larger for the between-category incongruity than the within-category incongruity (see also Torkildsen et al., 2007; Rämä et al., 2013). Rämä et al. (2013) in particular, presented 18- and 24-month-olds with an acoustic semantic priming task, where they heard pairs of words which were either taxonomically related (e.g., *train-bike*) or unrelated (e.g., *chicken-bike*). The N400-like priming effect was observed only in the 24-month-olds and in the 18-month-olds with higher expressive vocabulary. Similar to the results reported by Arias-Trejo & Plunkett (2011) and the results on phonological priming (Mani and Plunkett, 2010, 2011), these findings describe a developmental trend where children, by the end of their second year of life, are sensitive to the semantic links between words. This developing sensitivity to these links may, further, be keenly related to the vocabulary size of the children rather than merely chronological age (Rämä et al., 2013).

1.3. Vocabulary and lexical-semantic links in infancy

A number of studies on word recognition in infancy have found evidence of effects of infants' vocabulary size on the electrophysiological response to words in the infant brain. For example, as noted earlier, the N400-like response to semantically related words was modulated by children's vocabulary size at 18-months of age (Rämä et al., 2013). Similarly, in a longitudinal study, Borgström, Torkildsen and Lindgren (2015), found a relation between N400 amplitude to shape similarity between prime and target at 20-months and productive vocabulary size at 24-months. These results suggest that differences in sensitivity to shape similarity between words may be related to later lexical development. In another longitudinal study, Friederich and Friederici (2006) found that children, with a larger vocabulary size at 30-months of age, already displayed an N400 in conditions of lexical priming (e.g., naming *dog* while displaying the picture of a *dog*) at 19-months. Chow, et al. (2017) similarly report that individual differences in vocabulary size predicted better access to phonological and semantic information than participant's age at testing. Specifically, they found that 24- to 30-

month-olds with larger receptive vocabularies, were more likely to fixate a phonological distractor than children with smaller vocabularies. With a different sample (from 25- to 30-months-old), participants' expressive vocabulary size predicted toddlers' preference to fixate a thematically related distractor (Chow et al., 2017). These results suggest that children´s receptive and expressive vocabulary sizes may modulate their sensitivity to phonological and semantic links between words. A similar pattern is found in earlier studies: Mani & Plunkett (2011) report that the number of words known to children that overlapped with the target significantly impacted children's target recognition, suggesting again that the words understood by children that overlap along specific dimensions can modulate the phonological priming effects found. Mani & Huettig (2012) meanwhile report that sensitivity to the thematic links between verbs and their patients was modulated by the expressive vocabulary size of the children tested. Taken together, these studies suggest that individual variation in vocabulary size may, therefore, lead modulate sensitivity to phonological and semantic links between words in individual children, with potentially earlier sensitivity to such links in children with larger vocabularies. This highlights the need for a longitudinal investigation of the development of phonological and semantic links between words in young children, controlling, in particular for variation in individual vocabulary sizes.

Indeed, a wide corpus of research on the effects of infants' vocabulary on word recognition systematically suggests that higher vocabulary sizes in infancy correlate with higher accuracy and shorter reaction times in word recognition tasks (Fernald, Perfors, & Marchman, 2006). For instance, 18- to 21-month-olds with larger vocabularies were more accurate at recognizing a target based on partial phonetic information than their pairs with lower vocabulary (Fernald, Swingley & Pinto, 2001). This result indicates that efficiency in speech processing is correlated with a rich lexicon and that vocabulary size and accuracy in language processing may interact dynamically and in a cascaded manner generating consequences for subsequent real-time language processing and language learning.

1.4. The current study

The current study provides a longitudinal examination of developmental changes in children's sensitivity to phonological and semantic relatedness between words while controlling for individual differences in participants' vocabulary size. Previous research on phonological and semantic priming effects have worked with single age groups and used cross-sectional designs. To our knowledge, this is the first attempt to measure phonological and semantic priming effects longitudinally in infancy. Such a design, we argue, may allow us to better characterise children's developing sensitivity to phonological and semantic links in the early lexicon, with especial regard to role of chronological age and individual differences in children's vocabulary sizes in predicting such effects across development.

In our study, participants took part at three time points, at 18-, 21- and 24-months-old. We focused on these ages, because infants substantially increase their vocabulary during this period (Bates & Goldman, 1997; Fenson et al. 1994; Szagun, Stumper & Schramm, 2009) and previous studies have highlighted the development of priming effects between these ages (Arias-Trejo & Plunkett, 2009, 2013; Mani & Plunkett, 2010, 2011; Styles & Plunkett, 2009, 2011). In each session, participants were exposed to two phonological and semantic conditions each (related and unrelated), such that each participant saw four combinations of prime-target pairs, namely, phonologically related (*Phon-Rel*), phonologically unrelated (*Phon-Unrel*), semantically related (*Sem-Rel*) and semantically unrelated (*Sem-Unrel*).

Given the studies reviewed above, we expected to find early facilitation effects in phonological priming (at 18-months) that morph to interference effects at the later ages (21- to 24-months) tested, and the development of semantic priming effects only towards these later ages (Mani and Plunkett, 2010, 2011; Arias-Trejo & Plunkett, 2009, 2013). Furthermore, we also predicted effects of vocabulary size on word recognition with potentially earlier effects of semantic and phonological priming at each of the ages in children with larger vocabularies. Of interest is also the extent to which the finding of priming effects at the earlier ages modulates the priming effect at later ages, both within and across relatedness conditions, i.e., phonologically and semantically related trials.

2. Material and method

2.1. Participants

Data from 38 children (20 females, 18 males) from German-speaking families with typical development were included in the analysis. An additional 28 infants were excluded for further analysis due to: missing a follow up session (*n* = 13), missing follow up information (*n* = 2), auditory problems reported on the first session (*n* = 1), being exposed to more than 20 hours a week of another language at home (*n* = 3), technical problems (*n* = 1) or other exclusion criteria (*n* = 8; see subsection “Data Processing”). Participants were recruited from the laboratory database. Of the families included, 89.64% included families where one or both caregivers were in full or partial employment, 92.31% included families where one of both caregivers were college-educated. At the first session, infants were on average 18.19 months old (age range = 17.73 - 18.93); at the second session, they were on average 21.42 months old (age range = 20.53 - 22.73) and at the last session they were on average 24.65 months old (age range = 23.90 - 25.23). The Ethics Committee of the Institute for Psychology approved the study prior to the start of data collection.

2.2 Stimuli

Ninety-six nouns familiar to children from 18- to 24-months of age according to the Fragebogen zur Frühkindlichen Sprachentwicklung (FRAKIS; Szagun, et al., 2009) were selected as stimuli. With those words, we formed 32 triplets, each of which constituted the stimulus for a single trial.

Auditory stimuli were recorded by a native German female speaker using infant-directed speech. Prime words with their indefinite article were recorded in isolation and then inserted into one of three carrier phrases (i.e., “*Hey! Ich habe ein/e* [Prime]”, “*Wow! Ich sehe* *ein/e* [Prime]", or "*Huhh! Ich kaufe ein/e* [Prime]", Engl. "*Hey! I see a* [Prime]!", "*Wow! I have a* [Prime]!" or "*Huhh! I buy a* [Prime]!" respectively) where the word used as prime always occurred in the final position. Target words were similarly recorded in isolation and then inserted into the trial following the prime word in each condition. Auditory stimuli were subsequently processed using GoldWave software (St. John's, Newfoundland and Labrador, Canada). Three different prototypical images depicting the target and distractor labels on a grey background were chosen from public libraries available online, to ensure that children did not see the same image in each session. Images of the prime label were never presented to children. Images were edited using GNU Image Manipulation Program. Finally, using Video moviemaker, the auditory and visual stimuli were combined according to condition to create a separate video for each trial presented to children.

2.3. Apparatus

During the experiment, gaze data from both eyes were recorded using a Tobii X120 eye tracker. The videos were presented in the middle of a 40" screen located immediately above the eye tracker. The eye tracker was set to record gaze data at 60 Hz with an average accuracy of 0.5° visual angle. The Tobii Studio 3.3.2. Package was used to present videos to the children during the experiment. Prior to testing, participants were calibrated using a 5-point calibration procedure. The experiment started only when all points were successfully calibrated for both eyes. Loudspeakers hidden above the screen located to the left and right of the screen presented the auditory stimuli. Participants sat approximately 60 cm from the screen.

2.4. Procedure and Experimental Design

Due to the limited number of words familiar to children at 18-, 21- and 24-months-old, we repeated the presentation of a subset of words from session to session. At the first session, we presented 24 trials (six trials per type '*Phonological'* or '*Semantic'* and condition '*Related'* or '*Unrelated'*). We added eight trials in the subsequent sessions (two per type and condition), which included words typically acquired after 18-months of age. For the trial presentation, we followed a within-subjects design, where trials appeared in a pseudo-random order, with no more than three consecutive trials of the same type in succession. The order of trial presentation was different across sessions.

Each participant attended one session every three months, at 18-, 21- and 24-months of age. Prior to each visit, caregivers filled out a subset of the FRAKIS (Fragebogen zur fruhkindlichen Entwicklung) a German communicative inventory to provide us an estimate of participants' vocabulary size (Szagun, et al., 2009). At the beginning of each session, families were welcomed in the lab and were given a few minutes to familiarize themselves with the environment and experimenter. Once caregivers were informed about the goal and procedure of the study, they signed an informed consent form and filled out a questionnaire to provide us with information as to the socio-economic status of the family. Then one caregiver and the child were directed to the experimental booth. There, children were seated either in a car seat or on their caregivers' lap. In the latter case, the caregiver was given a pair of opaque glasses to wear or was asked to close their eyes to prevent the recording of their eye-movements. All caregivers were asked not to point at or repeat names of the words presented during the study. Participants were rewarded with a book upon completion of the study. This procedure was repeated in each session, which in total lasted approximately forty-five minutes.

In each session, participants were presented with four different kinds of trials which manipulated the relationship between the prime and target label presented (i.e., unrelated or related) and the kind of overlap between the target and prime (i.e., semantic or phonological). This resulted in four types of trials, namely, phonologically related (Phon-Rel), phonologically unrelated (Phon-Unrel), semantically related (Sem-Rel) and semantically unrelated (Sem-Unrel). See Tables 1 and 2 for a complete list of the word pairs used in the study at 18- months, 21- and 24-months respectively, as well as the pairing of word pairs across semantic and phonologically related and unrelated trials).

Table 1.

Triplets of prime- target and distractor labels used at the first session.

Phonological Priming				Semantical Priming			
Prime label	Unrelated label	Target Picture	Distractor Picture	Prime label	Unrelated label	Target Picture	Distractor Picture
Auto ‘car’	Trecker ‘tractor’	Auge ‘eye’	Bonbon ‘sweet’	Affe ‘monkey’	Löffel‘spoon’	Ente‘duck’	Bahn ‘train’
Ball ‘ball’	Haar ‘hair’	Banane ‘banana’	Uhr ‘clock’	Apfel‘apple’	Socke‘sock’	Milch ‘milk’	Windel ‘diaper’
Bauch ‘belly’	Katze ‘cat’	Baum ‘tree’	Stuhl ‘chair’	Bagger ‘excavator’	Affe ‘monkey’	Flugzeug ‘plane’	Lätzchen ‘bib’
Bus ‘bus’	Puppe ‘doll’	Buch‘book’	Keks‘cookie’	Brot ‘bread’	Vogel‘bird’	Eis ‘ice cream’	Telefon ‘phone’
Ei ‘egg’	Bauch ‘belly’	Eimer ‘bucket’	Decke ‘blanket’	Butter ‘butter’	Nase ‘nose’	Wurst ‘sausage’	Fliege ‘fly’
Finger ‘finger’	Bus ‘bus’	Fisch ‘fish’	Deckel ‘top lid’	Fuss ‘foot’	Apfel‘apple’	Ohr ‘ear’	Motorrad ‘motorcycle’
Haar ‘hair’	Müll ‘trash’	Hase ‘rabbit’	Joghurt ‘yoghurt’	Hund ‘dog’	Butter ‘butter’	Pferd ‘horse’	Schlüssel ‘key’
Katze ‘cat’	Ball ‘ball’	Kaffee ‘coffee’	Stein‘stone’	Löffel‘spoon’	Fuss ‘foot’	Tasse ‘mug’	Eule ‘owl’
Kuh ‘cow’	Finger ‘finger’	Kuchen ‘cake’	Lastwagen ‘lorry’	Nase ‘nose’	Hund ‘dog’	Arm ‘arm’	Saft ‘juice’
Müll ‘trash’	Ei ‘egg’	Mütze ‘cap’	Tiger ‘tiger’	Schuh‘shoe’	Brot ‘bread’	Hose ‘trousers’	Rutsche ‘slide’
Puppe ‘doll’	Auto ‘car’	Pullover ‘sweater’	Igel ‘hedgehog’	Socke‘sock’	Bagger ‘excavator’	Jacke ‘jacket’	Nudeln ‘pasta’

Trecker ‘tractor’	Kuh ‘cow’	Treppe‘stairs’	Blume ‘flower’	Vogel‘bird’	Schuh‘shoe’	Maus ‘mouse’	Tür ‘door’

Table 2.

Triplets of prime- target and distractor labels used at the second and third sessions.

Phonological Priming				Semantical Priming			
Prime label	Unrelated label	Target Picture	Distractor Picture	Prime label	Unrelated label	Target Picture	Distractor Picture
Auto ‘car’	Schaukel ‘swing’	Auge ‘eye’	Bonbon ‘sweet’	Affe ‘monkey’	Löffel‘spoon’	Ente‘duck’	Bahn ‘train’
Ball ‘ball’	Teddy‘teddy’	Banane‘banana’	Uhr‘clock’	Apfel‘apple’	Bein‘leg’	Milch‘milk’	Windel‘diaper’
Bauch‘belly’	Katze‘cat’	Baum‘tree’	Stuhl‘chair’	Bagger‘excavator’	Messer‘knife’	Flugzeug‘plane’	Lätzchen‘bib’
Bus‘bus’	Puppe‘doll’	Buch‘book’	Keks‘cookie’	Brot‘bread’	Vogel‘bird’	Eis‘ice cream’	Telefon‘phone’
Ei‘egg’	Bauch‘belly’	Eimer‘bucket’	Decke‘blanket’	Butter‘butter’	Nase‘nose’	Wurst‘sausage’	Fliege‘fly’
Finger‘finger’	Auto‘car’	Fisch‘fish’	Deckel‘top lid’	Fuss‘foot’	Apfel‘apple’	Ohr‘ear’	Motorrad‘motorcye’
Haar‘hair’	Ball‘ball’	Hase‘rabbit’	Joghurt‘yoghurt’	Hund‘dog’	Schuh‘shoe’	Pferd‘horse’	Schlüssel‘key’
Katze‘cat’	Haar‘hair’	Kaffee‘coffee’	Stein‘stone’	Löffel‘spoon’	Socke‘sock’	Tasse‘mug’	Eule‘owl’
Kuh‘cow’	Finger‘finger’	Kuchen‘cake’	Lastwagen‘lorry’	Nase‘nose’	Hund‘dog’	Arm‘arm’	Saft‘juice’
Müll‘trash’	Ei‘egg’	Mütze‘cap’	Tiger‘tiger’	Schuh‘shoe’	Butter‘butter’	Hose‘trousers’	Rutsche‘slide’
Puppe‘doll’	Becher‘glass’	Pullover‘sweater’	Igel‘hedgehog’	Socke‘sock’	Fuss‘foot’	Jacke‘jacket’	Nudeln‘pasta’

Trecker‘tractor’	Kuh‘cow’	Treppe‘stairs’	Blume‘flower’	Vogel‘bird’	Brot‘bread’	Maus‘mouse’	Tür‘door’
Becher‘glass’	Trecker‘tractor’	Bett‘bed’	Huhn‘chicken’	Bein‘leg’	Affe‘monkey’	Mund‘mouth’	Topf‘pot’
Schaf‘sheep’	Müll‘trash’	Schal‘scarf’	Ballon‘balloon’	Käse‘cheese’	Schwein‘pig’	Pommes‘french fries’	Lampe‘lamp’
Schaukel‘swing’	Bus‘bus’	Schaufel‘shovel’	Möhre‘carrot’	Messer‘knife’	Bagger‘excavator’	Flasche‘bottle’	Schnecke‘slug’
Teddy‘teddy’	Schaf‘sheep’	Teller‘plate’	Besen‘broom’	Schwein‘pig’	Käse‘cheese’	Elefant‘elephant’	Tisch‘table’

In *Phon-Rel* trials, we defined the phonological relationship between prime and target as words that shared the initial phonemes (C or CV), e.g., *Bauch-Baum* (Engl. tummy-tree; see Ramos-Sanchez & Arias-Trejo, 2018 for a similar approach). The *Sem-Rel* trials were formed by words which were exemplars from the same superordinate category but were not strongly associated with one another according to the Noun Associations for German database (Melinger & Weber, 2006). Importantly, targets and primes in *Phon-Rel* trials did not belong to the same superordinate category, nor were they associatively related, and nor were they visually similar. Targets and primes in *Sem-Rel* trials were phonologically unrelated and did not overlap along visual dimensions either, as for example *Löffel-Tasse* (Engl. spoon-cup). We used the same targets and primes in the unrelated pairs as in the related pairs ensuring that each prime was paired with a target which did not overlap either phonologically or semantically, i.e., did not overlap in their initial phonemes and formed part of different category groups. For example, *Bauch-Eimer* in the *Pho-Unrel* condition (Engl., stomach-bucket); and *Löffel-Ente* (Engl. spoon-duck) for the *Sem-Unrel* condition. The words used appear uniquely in one of the two relationships studied here, that is, either in the phonological condition (*Phon-Rel* or *Phon-Unrel*) or in the semantic condition (*Sem-Rel* or *Sem-Unrel*). Across sessions and participants, words were counterbalanced such that primes and target-distractor pairs appeared equally often in the related and unrelated conditions (within phonological or semantic lexical links). In addition, the side of presentation of the target picture side (left-right) was counterbalanced across infants.

A difference with other priming studies (Arias-Trejo & Plunkett, 2009, 2013; Mani & Plunkett, 2010, 2011) is that, nouns in German have obligatory grammatical gender (neutral, feminine or masculine) and gender-marker determiners that precede them. When selecting the triplets (prime-target-distractor), we ensured that prime and target did not uniquely overlap in gender, given that previous findings show gender based priming effects (Bobb & Mani, 2013). This was not always possible with the distractor. As a result, we produced four possible stimuli combinations: 1) all words had a different gender; 2) all words had the same gender – thus the target and distractor are similarly primed with regards to gender-; 3) target and distractor words had the same gender and it was different to prime gender; or 4) target and distractor had different gender which may overlap with prime (i.e., triplets Müll$_{m}$-Mütze$_{f}$-Tiger$_{m}$ and Butter$_{f}$-Pferd$_{n}$-Schlüssel$_{f}$; Engl. waste-hat-tiger and butter-horse-key, respectively). To ensure that the results were not skewed by such gender effects, the final analysis reported excludes these last trials.

We used an adaptation of the IPL paradigm similar to Arias-Trejo and Plunkett (2013) combined with eye tracking. Trial begin was manually controlled by the experimenter once the child fixated a green fixation cross at the centre of the screen. The trial began with the presentation of the carrier phrase containing the prime stimulus combined with the display of a centrally located black fixation cross. Importantly, the prime was presented in absence of any visual stimuli aside from the fixation cross. The prime label offset was timed at 2500ms from the trial onset. Following an interstimulus interval of 500ms (i.e., 3000ms into trial), the target label was presented. The target and distracter pictures followed and appeared after a stimulus onset asynchrony of 200ms (i.e., 3200ms into trial) and they remained on screen for 2500ms. Thus, the total duration of each trial was 5700ms (see Figure 1).

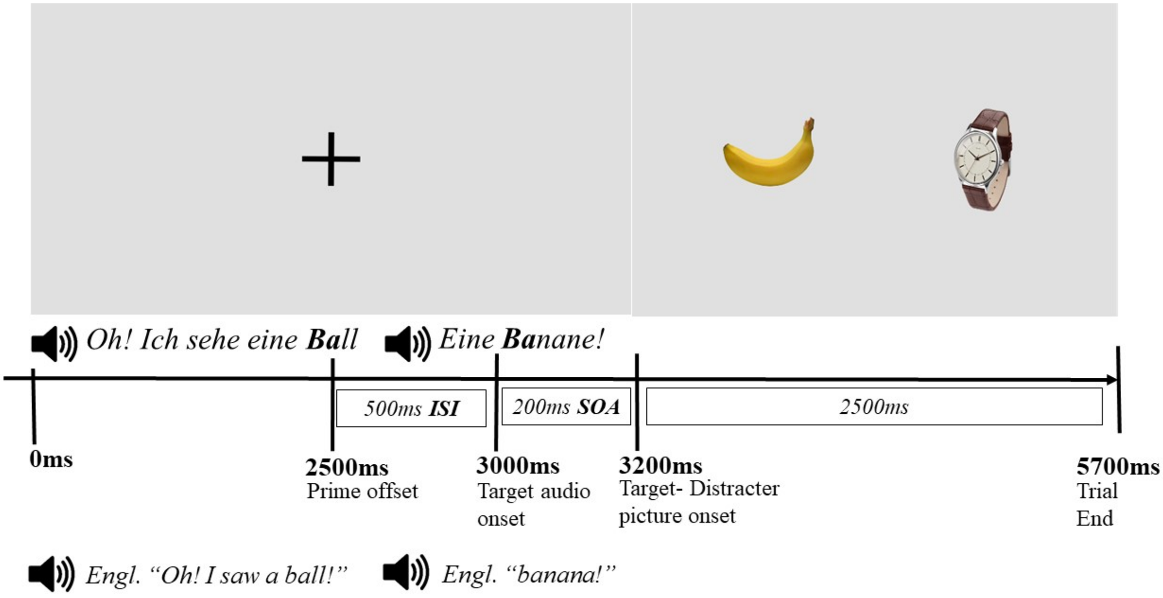

Figure 1. Trial stimuli sequence presentation.

2.5. Data processing

A custom code written in R (R Development Core Team, 2008) was used to process fixation data exported from the eye tracker. The eye-tracker provides an estimate of X and Y coordinates of children's fixations on the screen, with one data-point every 16ms. Data from time-stamps were only included when the eye tracker reliably acquired data from one or both eyes of the participant (validity less than 2 on Tobii scale) during picture presentation (i.e., 3200ms to 5700ms on trial). These timestamps were then divided into 40ms time bins (i.e., 63-time bins). Then, areas of interest (AOI) on the screen were defined according to the size of target and distractor images (i.e., 360 by 360 pixels) plus a frame of 60 pixels (up, down, left and right sides, i.e., 480 by 480 pixels), positioned to 360 pixels high on the monitor and with margin of 380 pixels between them. Based on these datapoints, we calculated our dependent variable, which is the proportion of target looking (PTL) by bin for each trial, namely the number of trials where children fixate the target at each time bin relative to the number of trials where children fixate the target and distractor. We only included data from

240ms to 2000ms after the onset of the pictures (3440-5200ms on trial, 45 bins) to ensure that only fixations that could reasonably be considered a response to stimulus presentation were included (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998).

We applied three trial exclusion criteria. First, we removed those trials in which infants fixated the screen less than 20% of the total duration of the trial (ca. 12 bins or 500ms). We applied this criterion to eliminate those trials in which participants were not on task (see Borovsky, Ellis, Evans, & Elman, 2016 for a similar approach). Second, we removed those trials in which participants fixated uniquely the target or uniquely the distractor during the presentation of the images. This was to ensure that we removed any trials where fixations may have been driven solely by children's visual preferences for one of the two displayed pictures. Third, as noted above, we excluded trials from the analysis where the gender of words was not adequately controlled. After applying these criteria, we excluded the data of eight participants, because they failed to provide at least one trial in all conditions (*Phon-Rel*, *Phon-Unrel*, *Sem-Rel* and *Sem-Unrel*) across the three sessions (18-, 21- and 24-months). In summary, we maintained 54,80% of the trials of the first session (n = 445); 64,65% of the trials of the second session (n = 717), and 70,99% of the trials of the third session (n = 815). The subsequent analyses were performed on the remaining data set. The issue of sparse data is a frequent inherent problem in infant research, but it is necessary to consider only those trials in the analysis, in which we can ensure that children were on task and that the effects are mediated mainly by the relationship between prime and target labels.

2.6 Statistical analysis

We report two analyses. First, we carried out a factorial mixed design ANOVA in R version 3.5.1 using ez package (version 4.4.-0; Bakeman, 2005) with separate subsets of data based on the type of link between prime and target (phonological and semantic trials). We introduced *Session* (18-, 21- and 24-months-old), and *Condition* (Related or Unrelated) as within-subjects factors and *Vocabulary Group* (Low or High) as between subjects-factor.

A second analyses used Growth Curve Analysis on the fixation data. This analysis has two advantages with relative to the traditional ANOVAs reported above. First, this allows us to capture variance between subjects across conditions (as a nested random effect), which is particularly important in such longitudinal data. Second, it allows us to enter both receptive and expressive vocabulary size into the model to tease apart the independent contributions of these two measures. We analysed the eye-tracking data using mixed-effects growth curve analyses with the proportion of target looking (PTL) at each time bin throughout the trial as the dependent variable (Mirman, Dixon, & Magnuson, 2008, see also Mirman, 2014). This statistical analysis was carried out in R using lme4 package (version 1.1-19; Bates, Mächler, Bolker, & Walker, 2015) to calculate two-level mixed-effects growth curve models with full information maximum likelihood estimation. The models compared each type of lexical link separately (i.e., *Phonologically Related* and *Unrelated* trials on the one hand and *Semantically Related and Unrelated* trials on the other). PTL across the 45 time bins were used as *Base model* observations. We modelled linear, quadratic and cubic terms to estimate the slope, acceleration and inflections in the extremities of the pattern of fixations across time. We used orthogonal polynomial transformations for the time bins at the linear, quadratic and cubic terms to ensure that time on trial was orthogonal to each other and the correlations between time elevated to the different exponentials do not arise due to the mere increase in the numbering. We included *Session* as a fixed effect to the *Base model* to account for the natural increase in accuracy in word recognition achieved by children across sessions. The *Unrelated* trials in the factor *Condition* and the *18-months* level in the factor *Session* were treated as the baseline for parameter estimations. We included *Participants* and nested effects of *Participant* and *Condition* across all models as random effects. Both random effects were nested within the *Linear* and *Quadratic* temporal terms to capture the variance associated with each participant at acceleration and the central curve inflection on target recognition through the trial. We added the random effect *Participant:Condition* to provide information about the variability associated with the dependency of the PTL on each condition contributed by each participant for a given time bin. Further Level-2 models were computed to determine whether adding *Condition* (*Related* against *Unrelated* trials) provided a better statistical model fit of the data. Next, additional models were calculated including either the participant´s *Receptive* or *Expressive Vocabulary Size,* to estimate the improvement of the model when including those factors. Changes in model fit were evaluated using -2 times the change in log-likelihood, which is distributed as chi χ^2 with degrees of freedom equal to the number of parameters added for each comparison. Statistical significance (*p*-values) for individual parameter estimates were assessed using the normal approximation (i.e., treating the *t*-value as a *z*-value).

Finally, we calculated correlations between the random effects estimated at the linear and quadratic temporal term for each type of lexical link (Phonological and Semantic) within sessions, to determine whether performance on each lexical link correlate with performance on the other type of lexical link.

3. Results

3.1. Phonological Related and Unrelated Trials

Firstly, a factorial mixed design ANOVA was carried out on the phonologically related and unrelated trials with *Session* (18-, 21- and 24-months-old), and *Condition* (Related or Unrelated) as within-subjects factors; and *Vocabulary Group* (Low or High) as between subjects-factor. The factor *Vocabulary Group* was defined by the median split of the sum of the receptive vocabulary size in each session. Here effects sizes are indicated by the generalized eta-squared produced by the ezANOVA function. There was no significant effect of *Session* $F(2,72) = 0.36$, $p = .69$, $r = .00$; *Condition* $F(1,36) = 1.87$, $p = .18$, $r = .01$ or *Vocabulary Group* $F(1,36) = 1.02$, $p = .32$, $r = .00$. There was no significant interaction between *Session* and *Condition* $F(2,72) = 0.01$, $p = .99$, $r = .00$; nor between *Session* and *Vocabulary Group* $F(2,72) = 0.96$, $p = .39$, $r = .01$; and nor between *Session* by *Condition* by *Vocabulary Group* $F(2,72) = 0.21$, $p = .81$, $r = .00$. However, there was a significant interaction between *Condition* and *Vocabulary Group* $F(1,36) = 4.84$, $p = .03$, $r = .02$. As the means plotted in Figure 2 suggest, overall, the proportion of target looking is modulated by participants' receptive vocabulary size and the condition (related, unrelated). In particular, overall, participants with lower receptive vocabulary sizes fixated the target more robustly when primed by a phonologically related prime relative to an unrelated prime, $F(1,18) = 6.93$, $p = .02$ (see Figure 2). Paired *t*-test comparing the two conditions separated by high ($t(18) = -0.56$, $p = .58$, $r = .13$) and low ($t(18) = 2.63$, $p = .02$, $r = .53$) receptive vocabulary size across sessions, reveal overall phonological priming effects in lower receptive vocabulary participants (*Pho-Rel* $M = 0.56$, $SE = 0.01$ and *Pho-Unrel* $M = 0.51$, $SE = 0.01$).

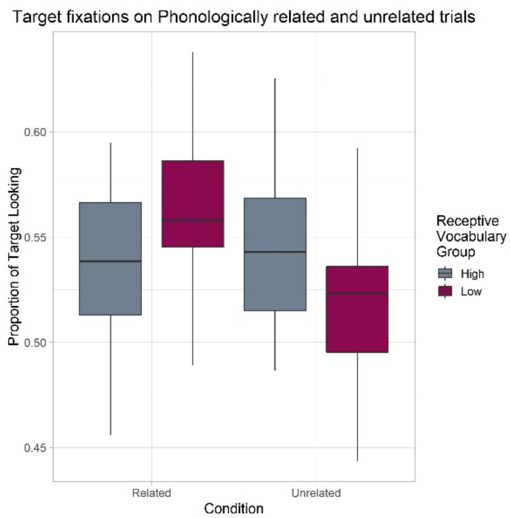

Figure 2. Means of proportions of target looking for the phonologically related and unrelated trials, grouped by condition and receptive vocabulary group (low in dark pink, and high in grey).

Separated repeated-measures ANOVAs per session were carried out with *Condition* as within-subjects factor and *Vocabulary Group* as between subjects-factor. In this analysis, the factor *Vocabulary Group* was defined by the median split of participants receptive vocabulary size in that session. Table 3 offers a description of participants vocabulary size in each session.

Table 3

Participants receptive and expressive vocabulary size.

Age in	Receptive vocabulary size				Expressive vocabulary size			
months	Med	M	SD	Range	Med	M	SD	Range
18	240	257.03	116.29	44 - 599	25	54.81	59.35	0 - 286
21	416	405.24	96.29	167 - 599	156	166.97	130.93	4 - 426
24	521	501.97	73.41	275 - 599	393	393.5	172.46	10 - 591

At 18-months-old, there was no significant effect of *Condition* ($F(1,36) = 0.45$, $p = .51$, $r = .01$), nor of *Vocabulary Group* ($F(1,36) = 2.62$, $p = .11$, $r = .03$); and there was no significant interaction between *Condition* and *Vocabulary Group* ($F(1,36) = 0.04$, $p = .84$, $r = .00$). At 21-months-old, there was no significant effect of *Condition* ($F(1,36) = 0.54$, $p = .47$, $r = .01$) nor of *Vocabulary Group* ($F(1,36) = 1.34$, $p = .25$, $r = .01$). However, there was a significant interaction between *Condition* and *Vocabulary Group* $F(1,36) = 6.02$, $p = .02$, $r = .10$. Similar to the results at 18-months-old, at 24-months-old, there was no significant effect of *Condition* ($F(1,36) = 0.92$, $p = .34$, $r = .01$). There was a marginally significant effect of *Vocabulary Group* ($F(1,36) = 4.01$, $p = .05$, $r = .05$); and there was no significant interaction between *Condition* and *Vocabulary Group*($F(1,36) = 2.44$, $p = .13$, $r = .03$).

Planned post hoc comparisons show no statistical differences between means of target fixations in *Related* and *Unrelated* trials at 18-months-old in children with *High* ($t(18) = 0.37$, *p* = .71, *r* = .09) or *Low Vocabulary* (*t*(18) = 0.56, *p* = .58, *r* = .03). At 21-months-olds, paired *t*-tests revealed no statistical differences on means of target fixations between *Related* and *Unrelated* trials in children with *High Vocabulary* (*t*(18) = -1.59, *p* = .13, *r* = .35) and a trend towards a significant difference between the two trial types in children with *Low Vocabulary* (*t*(18) = 1.89, *p* = .07, *r* =.41). That is, at 21-months-old, there was weak support for the conclusion that participants with lower receptive vocabulary size fixated the target more when primed by a phonologically related prime (see Figure 3). At 24-months-old, there were no statistical differences between means of target fixations on *Related* and *Unrelated* trials in children with *High Vocabulary* (*t*(18)= -0.36, *p* = .73, *r* = .08). However, toddlers with *Low Vocabulary sizes*, fixated the target more when presented with a related prime relative to an unrelated prime, (*t*(18) = 2.38, *p* = .03, *r* = .49; see Figure 4).

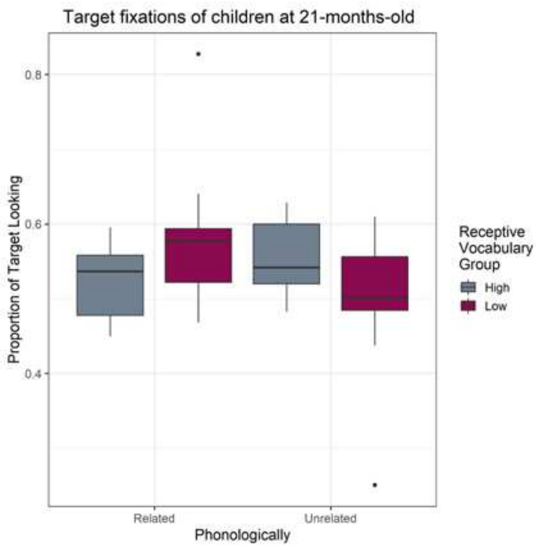

Figure 3. Means of proportions of target looking at 21-months-old for phonologically related and unrelated trials, grouped by condition and receptive vocabulary group (low in dark pink, and high in grey).

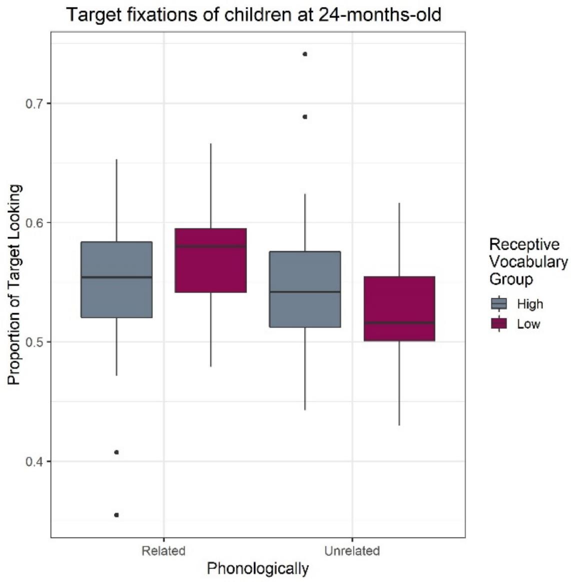

Figure 4. Means of proportions of target looking for phonologically related and unrelated trials of participants with higher (grey) and lower (dark pink) receptive vocabulary size at 24-months-old.

Due to the limitations of the analysis of variance as a method to account for the subtle changes as the trial unfolds, and to tease apart the effects of receptive and expressive vocabulary size further we carried out GCA with the data. In addition to the base model, three separate models were computed: 1) *Condition Model*: a model adding to the Base Model, the fixed and interaction terms of *Condition*, 2) *Receptive Vocabulary Model*: a model adding to the Condition Model, the fixed and interaction effects of *Condition* and children´s *Receptive Vocabulary Size;* and 3) *Expressive Vocabulary Model:* a model adding to the Condition Model, the fixed and interaction effects of *Condition* and children´s *Expressive Vocabulary Size*. The *Condition Model* was compared against the *Base model* and the *Vocabulary* models were compared to the *Condition Model*. While all factors improved the fit of the model, the model including *Condition* and *Receptive Vocabulary Size* offered the best fit for data from the phonologically related and unrelated trials, as indicated in the Log-Likelihood ratio (see

Table 5 for additional information regarding model fit comparisons). Thus, despite controlling for age, the model found that adding participants' *Receptive Vocabulary Size* improved model fit. Vocabulary size is, therefore, a strong predictor of the priming effects over and above chronological age.

Table 5.

Model comparison and measures of model fit for the Phonologically Related and Unrelated trials.

Statistic	Base Model	Condition Model	Receptive Vocabulary Model	Expressive Vocabulary Model
LL	1841.23	1884.40	**2019.38**	2014.51
χ^2	-	86.34	269.94	260.21
Df χ^2	-	12	24	24
P	-	0.00 ***	0.00***	0.00***

Note: log-likelihood (LL), Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

The parameter estimates and their standard errors along with p-values (estimated using the normal approximation for the t-values) are derived from the model that included *Receptive Vocabulary Size Model* (see Appendix A for the detailed model output). Given our focus on examining phonological priming across development, we list here only terms that interact with Condition.

Here, we will walk through the significant terms in the model reported in Appendix A, focussing mainly on the effects under investigation in the study. The significant effect of *Condition* (Pho-Unrel vs. Pho-Rel) at the *Intercept*, the *Quadratic* and *Cubic* temporal terms reveal that the overall height, central inflections and extremities of fixations differ significantly between phonologically related and unrelated trials, with an overall phonological facilitation effect on word recognition.

The significant interactions between age (*18-* vs. *24-months-old)* and *Condition* at the *Quadratic* and *Cubic* temporal terms and the significant interaction between age (*21-* vs. *24-months-old)* and *Condition* at the *Quadratic* temporal term reveal differences in the phonological priming effect across age-groups. The significant interaction between *Condition* and *Receptive Vocabulary size* at the *Intercept,* the *Quadratic* and *Cubic* temporal terms suggest differences in target recognition across condition based on the vocabulary size of the children. The significant interactions between age (*18- vs. 24-* and *21- vs. 24- months*), *Condition* and *Receptive Vocabulary size* at the *Intercept*, *Linear*, *Quadratic* and *Cubic* temporal terms suggest differences in phonological priming effects based on the age and vocabulary size of the children tested.

Splitting by children's receptive vocabulary size across sessions (i.e., *Low* vs. *High*; see Appendix B for the model fits for children with lower and higher vocabulary size. The results of the *Condition Model* applied to the data of children with *Low vocabulary size* revealed significant effects of *Condition* at the *Intercept* on target fixations (estimate = -.02, p = .02). Fitting the *Condition Model* to the data of children with *High vocabulary size* found no significant effects of *Condition* on any of the temporal terms. These results suggest that participants with lower receptive vocabulary size showed increased target fixations in phonologically related trials relative to unrelated trials (see Figure 5, lower panel), while participants with higher receptive vocabulary sizes did not.

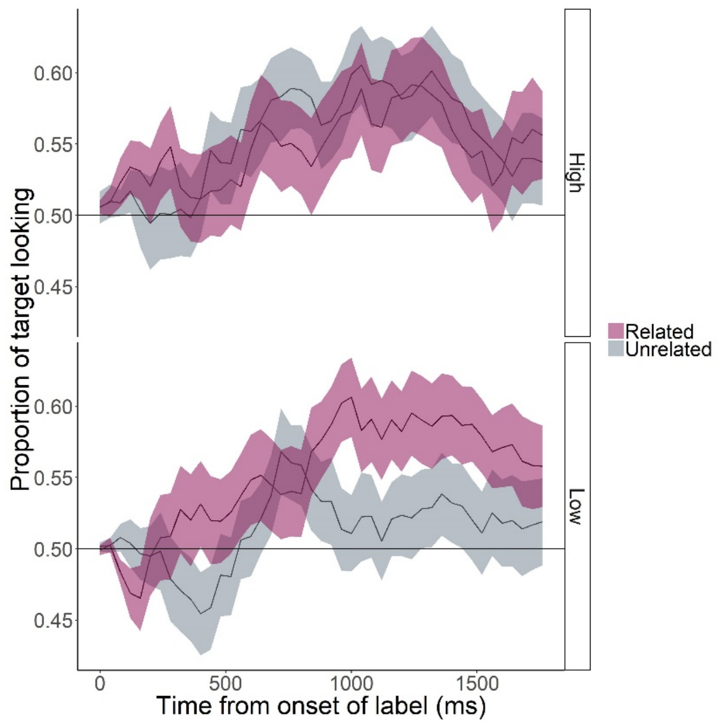

Figure 5. Target fixations in phonologically related and unrelated trials separated by Receptive Vocabulary Size (High and Low). For clarification, participants were grouped according to their receptive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 240, $Med_{21\text{-mo}}$ = 416, and $Med_{24\text{-mo}}$= 521).

Further age-wise comparisons were performed adjusting the Receptive Vocabulary Model to the subset of data at 18-, 21- and 24-months-old (see results in Appendix C). At *18-months*, there was a significant effect of *Condition* at the *Cubic* temporal term (estimate = -0.09, p < .01), suggesting that, at 18-months, children display early subtle target fixation curves above chance level on phonologically related trials relative to unrelated trials (see Appendix D.

At *21-months*, there was a significant effect of *Condition* at the *Cubic* (estimate = 0.05, p < .00) temporal term and a significant interaction between *Condition* and *Receptive Vocabulary size* at the *Intercept* (estimate = 0.04, p < .00), *Quadratic* (estimate = -0.18, p <

.01) and *Cubic* (estimate = 0.05, $p < .04$) temporal terms. Splitting by *Receptive Vocabulary size*, we found significant effects of *Condition* at the *Intercept* (estimate = -0.03, $p = .02$) and *Cubic* (estimate = -0.05, $p = .01$) temporal terms in children with lower receptive Vocabulary sizes and significant effects of *Condition* at the *Quadratic* (estimate = -0.14, $p = .02$) and *Cubic* (estimate = 0.18, $p < .00$) temporal terms in children with higher receptive vocabulary sizes. These results suggest that at 21-months, children with higher receptive vocabulary size show phonological interference effects (Figure 7) while children with lower receptive vocabulary size show phonological facilitation effects (Figure 6).

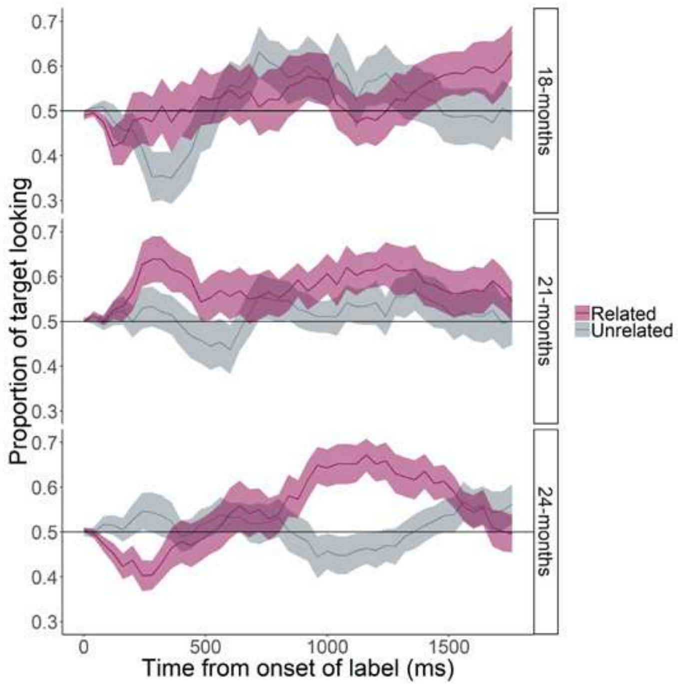

Figure 6. Target fixations in phonologically related and unrelated trials separated by age (18-months, 21-months, 24-months) for children from the *Low Vocabulary Size* group. For clarification, participants were grouped according to their receptive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 240, $Med_{21\text{-mo}}$ = 416, and $Med_{24\text{-mo}}$= 521).

Finally, at *24-months-old*, there was a significant effect of *Condition* at the *Linear* (estimate = -0.25, $p < .05$), *Quadratic* (estimate = 0.23, $p < .03$) and *Cubic* temporal terms (estimate = 0.28, $p < .00$) and a significant interaction between *Condition* and *Receptive Vocabulary size* at the *Linear* (estimate = 0.30, $p < .02$) and *Cubic* (estimate = -0.28, $p < .00$) temporal terms. Splitting by *Receptive Vocabulary size*, we found significant effects of *Condition* at the *Cubic* (estimate = -0.11, $p < .00$) temporal term in children with higher receptive vocabulary sizes and significant effects of *Condition* at the *Quadratic* (estimate = 0.19, $p < .01$) and *Cubic* (estimate = 0.19, $p < .00$) temporal terms in children with lower expressive vocabulary sizes. Similar to the 21-month-olds, at 24-months, participants with higher vocabulary size show phonological interference effects (Figure 7), while participants with low receptive vocabulary size show phonological facilitation effects on word recognition (Figure 6).

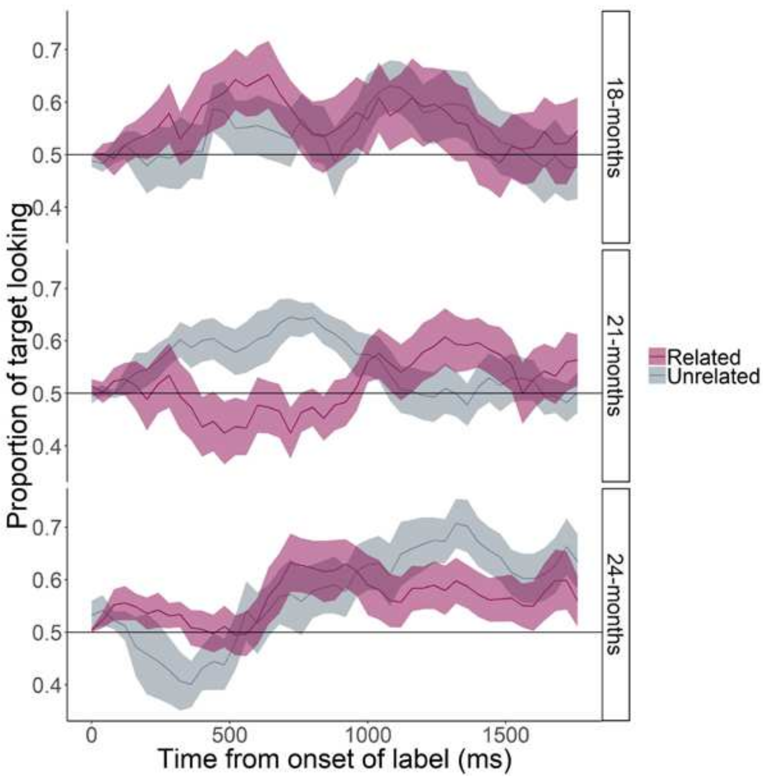

Figure 7. Target fixations in phonologically related and unrelated trials separated by age (18-months, 21-months, 24-months) for children from the *High Vocabulary Size* group. For clarification, participants were grouped according to their receptive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 240, $Med_{21\text{-mo}}$ = 416, and $Med_{24\text{-mo}}$= 521).

To summarize the results of both analyses, we find different patterns of target recognition in phonologically related and unrelated words, depending on children's receptive vocabulary size. Both the traditional analyses and the GCA suggest that at 21-months, children with low vocabulary size show phonological facilitation effects, with increased fixations to the target in phonologically related trials compared to unrelated trials. In addition, the results of the GCA suggested that children with high vocabulary size show a phonological interference effect at 21-months, and an early phonological facilitation and later interference effect at 24-months. At 18-months, we found only a significant effect of condition with no interaction between condition and vocabulary size.

3.2. Semantic Related and Unrelated Trials

Considering only semantically related and unrelated trials, we implemented the same factorial mixed design ANOVA, described in the previous section, with *Session*, and *Condition* as within-subjects factors and *Vocabulary Group* as between subjects-factor. Importantly, all ANOVAs were carried out with receptive vocabulary size to maintain consistency with the analyses of phonological priming effects. There was a significant effect of *Condition* $F(1,36) = 6.01$, $p = .02$, $r = .02$ and *Vocabulary Group* $F(1,36) = 5.21$, $p = .03$, $r = .02$; but there was no significant effect of *Session* $F(2,72) = 0.24$, $p = .79$, $r = .00$. There were no significant interactions between *Condition* and *Vocabulary Group* $F(1,36) = 0.29$, $p = .59$, $r = .00$; nor between *Session* and *Condition* $F(2,72) = 0.80$, $p = .45$, $r = .01$; nor between

Session and *Vocabulary Group* $F(2,72) = 0.79$, $p = .46$, $r = .01$; neither between *Session* by *Condition* and *Vocabulary Group* $F(2,72) = 1.52$, $p = .22$, $r = .02$.

Additional repeated-measures ANOVAs were carried out per session with *Condition* as within-subjects factor and *Vocabulary Group* as between subjects-factor. At 18-months, there was a marginally significant effect of *Condition* ($F(1,36) = 4.26$, $p = .05$, $r = .05$) and no significant effect of *Vocabulary Group* ($F(1,36) = 1.29$, $p = .26$, $r = .02$) or a significant interaction between *Condition* and *Vocabulary Group* ($F(1,36) = 0.38$, $p = .54$, $r = .00$). At 21-months, there was no significant effect of *Condition* ($F(1,36) = 1.92$, $p = .17$, $r = .03$) nor of *Vocabulary Group* ($F(1,36) = 1.04$, $p = .31$, $r = .01$); and there was no significant interaction between *Condition* and *Vocabulary Group* ($F(1,36) = 1.41$, $p = .24$, $r = .02$). Similarly, at 24-months, there was no significant effect of *Condition* ($F(1,36) = 0.10$, $p = .75$, $r = .00$), *Vocabulary Group* ($F(1,36) = 0.21$, $p = .64$, $r = .00$) or of the interaction between *Condition* by *Vocabulary Group* ($F(1,36) = 2.62$, $p = .11$, $r = .05$).

Planned post hoc comparisons show that there were no statistical differences between means of PTL at 18-months between *Related* and *Unrelated* trials in children with *High* ($t(18)= -1.57$, $p = .13$, $r = .35$) or *Low Vocabulary* ($t(18)= -1.39$. $p = .18$, $r = .31$). Also, at 21-months, there was no statistical difference on PTL between *Related* and *Unrelated* trials in children with *High Vocabulary* ($t(18)= -0.14$, $p = .89$, $r = .03$), or *Low Vocabulary* ($t(18) = -1.75$, $p = .10$, $r =.38$). Alike, at 24-months, there was no statistical difference between means on PTL on *Related* and *Unrelated* trials in children with *High* ($t(18) = 1.14$, $p = .27$, $r = .26$) or *Low Vocabulary* ($t(18) = -1.18$, $p = .25$, $r = .27$).

Next, we carried out GCA to describe the temporal changes on target fixation curves on semantically related and unrelated trials. The same model structure and comparisons, described in the previous section, were performed on semantically related and unrelated trials. From model fits comparisons, the *Expressive Vocabulary Model* was the one which offered the best fit to the data, as indicated in their highest Log-Likelihood ratio (see Table 6). This presents a stark contrast to the data entered into the ANOVA, where we entered receptive vocabulary size as a factor to maintain consistency with the phonological priming analyses. However, we find that adding *Expressive Vocabulary size* improved model fit over and above effects of chronological age.

Table 6.

Model comparison and measures of model fit for the Semantic related and unrelated trials.

Statistic	Base Model	Condition Model	Receptive Vocabulary Model	Expressive Vocabulary Model
LL	909.26	930.37	1028.15	**1138.58**
χ^2	-	42.23	195.55	416.42
Df χ^2	-	12	24	24
p	-	0.00***	0.00***	0.00***

Note: log-likelihood (LL), Signif. codes: 0.001 '***' 0.01 '**

The parameter estimates and their standard errors along with p-values are derived from the model that included *Expressive Vocabulary Size* (see Appendix E for detailed model output). Given our interest in examining semantic priming, we list here only interactions with condition. The results of the model including *Expressive Vocabulary size* and *Condition* found no significant effect of *Condition* (Sem-Unrel vs. Sem-Rel trials) on any of the time terms. However, there was a significant interaction between age (*18- vs. 24-months-old*) and *Condition* at the *Intercept*, and *Linear* temporal term. There was also, a significant interaction between age (*21- vs. 24-months-old)* and *Condition* at the *Linear* and *Cubic* temporal terms. These interactions reveal differences in the semantic priming effect across age-groups. There was a significant interaction between *Condition* and *Expressive Vocabulary* size at the

Intercept, *Linear*, *Quadratic* and *Cubic* temporal terms, suggesting differences in the semantic priming effect across children of different vocabulary sizes (see Figure 8). There was a significant interaction between *21- vs. 24-months* by *Condition* by *Expressive Vocabulary size* at the *Intercept* and *Quadratic* temporal term and a significant interaction between *18- vs. 24-months-old* by *Condition* by *Expressive Vocabulary size* at the *Linear* temporal term. These interactions suggest differences in children's priming effects across age-groups depending on their vocabulary size.

Further GCA were performed with subset of data according to children expressive vocabulary size within session (i.e., *Low* vs. *High,* see Appendix F). The results of the *Condition Model* applied to the data of children with *Low vocabulary size* revealed no significant effects of *Condition* on target fixations. Fitting the *Condition Model* to the data of children with *High vocabulary size* found a significant effect of *Condition* at the *Intercept* (estimate = 0.02, $p < .02$). These results suggest that participants with higher expressive vocabulary size showed increased target fixations in semantically unrelated trials relative to related trials (see Figure 8, upper panel), while participants with lower expressive vocabulary sizes did not.

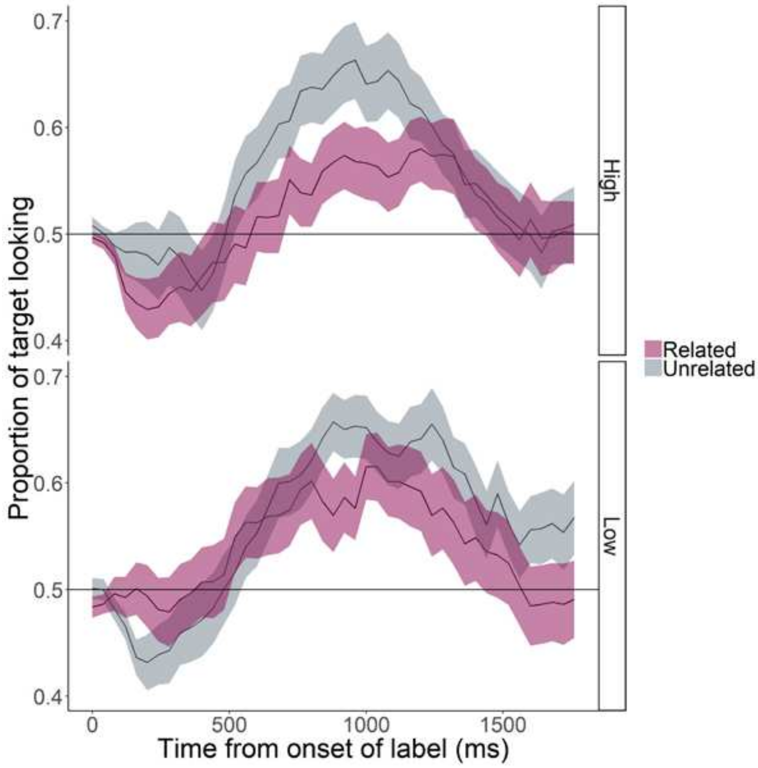

Figure 8. Target fixations in semantically related and unrelated trials separated by Expressive Vocabulary Size (High and Low). For clarification, participants were grouped according to their expressive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 25, $Med_{21\text{-mo}}$ = 156, and $Med_{24\text{-mo}}$= 393).

Supplementary GCA were performed adjusting the *Expressive Vocabulary Model* to subset of data according to children age in each *Session* (i.e., *18-, 21-* and *24-months-old*, see Appendix G). At *18-months*, there was a significant effect of *Condition* at the *Cubic* (estimate = 0.15, p = .01) temporal term and a significant interaction between *Condition* and *Expressive Vocabulary size* at the *Cubic* (estimate = 0.20, p = .00) temporal term. Thus, overall, 18-month-olds show a significant semantic interference effect, with increased fixations to the target in semantically unrelated trials relative to related trials. While the interaction between *Condition* and *Expressive Vocabulary* suggests differences in the semantic interference effects across vocabulary groups, subsequent tests revealed no significant effects of *Condition* in data split by vocabulary size (i.e., splitting by *Expressive Vocabulary size*, at 18-months-old we found no significant effects of *Condition* at any temporal term in children with lower or higher expressive vocabulary size).

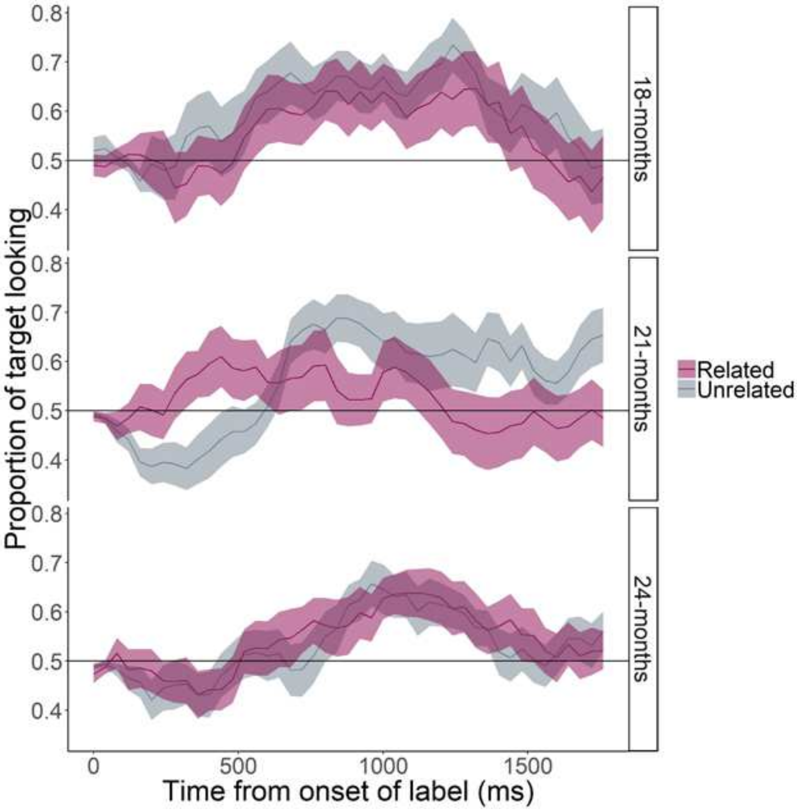

Figure 9. Target fixations in semantically related and unrelated trials separated by age (18-months, 21-months and 24-months) for children with low expressive vocabulary sizes. For clarification, participants were grouped according to their expressive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 25, $Med_{21\text{-mo}}$ = 156, and $Med_{24\text{-mo}}$= 393).

At *21-months*, there was a significant effect *Condition* at the *Cubic* (estimate = -0.04, p = .03) temporal term and a significant interaction between *Condition* by *Expressive Vocabulary size* at the *Cubic* (estimate = 0.12, p < .00) temporal term. Splitting by *Vocabulary size*, we found significant effects of *Condition* at the *Linear* (estimate = 0.28, p =

.04) and *Cubic* (estimate = -0.14, $p < .00$) temporal term in children with lower expressive Vocabulary sizes (see Figure 9), but not in children with higher expressive vocabulary sizes (see Figure 10).

Lastly, at *24-months*, there was a significant effect of *Condition* at the *Cubic* (estimate = 0.04, $p = .04$) temporal term and a significant interaction between *Condition* and *Expressive Vocabulary size* at the *Cubic* (estimate = -0.04, $p < .00$) temporal term. Splitting by *Vocabulary size*, we found significant effects of *Condition* at the *Quadratic* (estimate = -0.14, $p = .04$) temporal term in children with higher expressive vocabulary sizes (see Figure 10), but not in children with lower expressive vocabulary sizes (see Figure 9).

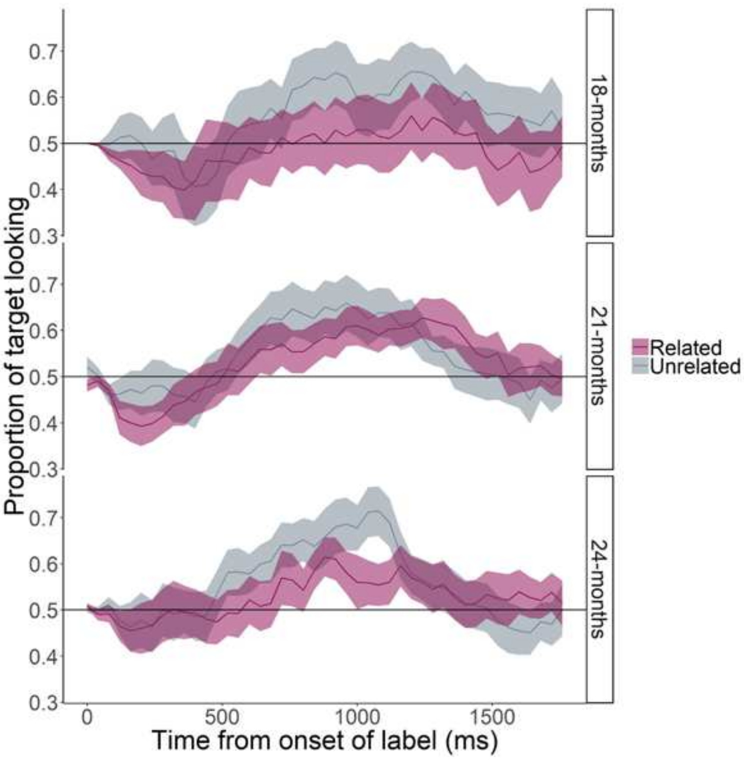

Figure 10. Target fixations in semantically related and unrelated trials separated by age (18-months, 21-months and 24-months) for children with high expressive vocabulary sizes. For

clarification, participants were grouped according to their expressive vocabulary median split at each session (i.e., $Med_{18\text{-mo}}$= 25, $Med_{21\text{-mo}}$ = 156, and $Med_{24\text{-mo}}$= 393).

To summarize, the traditional analyses revealed a main effect of Condition with increased target fixations in semantically unrelated trials relative to related trials, i.e., an overall semantic interference effect with no modulation of this effect by vocabulary size or age. The GCA allowed us greater precision in the modulation of this effect across age-groups and vocabulary groups. In particular, we found that children with high vocabulary sizes showed a semantic interference effect, while children with lower vocabulary sizes did not.

Furthermore, while the 18-month-olds showed an overall effect of *Condition* (i.e., an overall semantic interference effect), as in the traditional analyses, at 21- and 24-months, we found different results based on the vocabulary sizes of the children tested. In particular, at 21-months, we found semantic interference effects only in children with lower vocabulary sizes, at 24-months, we found the same only in children with higher vocabulary sizes.

3.3. Correlations between lexical links

The time course of target fixation was modelled using growth curve analysis with three-order orthogonal polynomials. Separated models were fit for each *Session* and *Type of lexical link* (Phonological and Semantic) with the fixed effects of *Condition* (Related vs. Unrelated) and *Receptive* or *Expressive vocabulary size* (for the phonological and semantic trials, respectively) on all temporal terms; and with *Participant*, and *Participant* by *Condition* random effects on the linear and quadratic temporal terms. The participant by condition random effect estimates were used to compute individual participant effect sizes estimates for each participant, subtracting the random effect estimates of related minus unrelated trials. We focused our analysis on the intercept, linear and quadratic temporal terms to evaluate the correlations on sensibility to the phonological and semantic lexical links between sessions and lexical links. The results show no significant correlations between the *Phonological* and *Semantic* links at the *Intercept*, *Linear* or *Quadratic* temporal terms, *ps* >.05. Also, there were no significant correlations within the *Phonological lexical link* across sessions, *ps* >.05. Along the same lines, there are no significant correlations within the *Semantic lexical link* across sessions, *ps* >.05 (see Appendix H). These results indicate, contrary to our expectations, there was no correlation between participants' sensitivity to phonological priming and semantic priming modulations across sessions or between lexical links across sessions.

4. Discussion

The current study aimed at a longitudinal assessment of phonological and semantic priming effects in early childhood, with a particular focus on the role of children's vocabulary size on the development and direction of these effects. Overall, the results suggest variation in priming effects according to children's vocabulary size, although this effect was more consistent across analyses with regards to phonological priming relative to semantic priming.

With regards to phonological priming, we found that children with low vocabulary sizes, in general, showed a phonological facilitation effect (both overall and at 21- and 24-months, but not at 18-months), while children with high vocabulary sizes showed either no effect or an interference effect (depending on the analyses). In particular, we found that controlling for age, vocabulary size of the children improved the model fit to the data in interaction with condition. Eighteen-month-olds showed an overall facilitation effect that did not interact with vocabulary size. In particular, according to both the traditional analyses and the GCA we found that while all 18-month-olds shows an overall phonological facilitation effect, only children with lower vocabulary show phonological facilitation effect at 21- and 24-months of age. According to the GCA, children with high vocabulary sizes showed phonological interference effects. This replicates the pattern of effects in the literature with remarkable consistency, while triggering further discussion with regards to the underpinnings of these effect reversals. In particular, Mani & Plunkett (2010, 2011) showed that 18-month-olds had an overall facilitation effect in phonological priming tasks, while the interference effect at 24-months was modulated by the cohort size of the individual words tested. Extending the previous results in the literature, the current findings suggest a keen role for vocabulary size in the direction of phonological priming effects, with larger vocabularies leading to interference in target recognition in primed trials and smaller vocabularies leading to facilitation in target recognition in primed trials. This explanation is also consistent with a recent simulation of early word recognition, suggesting the absence of lexical competition at early ages (18-months), and the development of such competition effects between 21- to 24-months of age (Mayor & Plunkett, 2014). Here, we extend this explanation beyond the ages of the infants tested, but rather to the vocabulary sizes of the children to show that children with low vocabularies do not display lexical competition effects in phonological word recognition while children with larger vocabularies, presumably triggered by their larger vocabularies, do show such interference effects. This finding makes intuitive sense, highlighting the fact that the rapidly expanding vocabulary between 18- to 24-months underlies the differences in the priming effects reported to-date. Importantly, applying a longitudinal design (where we tested the same participants at different time points) offered us a unique overview of the interaction between children's pace of words acquisition and words recognition skills across development. Thus rather than highlighting particular age-groups at which certain changes take place, here we show that the development of phonological priming effects is a gradual process across the early months with increasing changes in vocabulary size triggering changes in the pattern of responding.

Before we discuss the modulation of the semantic priming effect by vocabulary size, we flag here an important concern with our findings, namely the fact that in contrast to most of the previous literature on semantic priming, we consistently find here a semantic interference effect. In other words, we find that children look longer at the target in semantically unrelated trials relative to semantically related trials. This was consistent across both the analyses reported in the paper and the robustness of this effect is clear from Figure 8. This is in contrast to most of the literature on semantic priming effects in early development (Arias-Trejo & Plunkett, 2009, 2013; Styles and Plunkett, 2009, 2011; Torkildsen et al., 2007; Rämä et al., 2013). The only consistency with the literature is the finding that children in a Head Turn Preference Task listened longer to trials presenting children with unrelated stimuli relative to related stimuli (Willits et al., 2013), and with a recent study which found backward semantic inhibitory effects in 18-months toddlers with higher vocabulary (Chow, Aimola Daivies, Fuentes & Plunkett, 2018). While we see no reason why our findings should pattern with a different paradigm relative to the one employed in the current study, we highlight some possible reasons for this difference. First, we highlight the timing of presentation of the stimuli. In particular, due to the fact that German nouns must be preceded by a gendered article, the interstimulus interval between prime and target in the current study was increased relative to previous semantic priming studies, e.g., this was 200ms in Arias-Trejo & Plunkett (2009, 2013) relative to the 500ms in the current study. While this reasoning is speculative, we suggest that either the introduction of the gender-inflected article and/or the increased delay between the prime and the target may have led to the differences in the direction of the effect reported here. More importantly, we note that we find a systematic semantic interference using only taxonomically related pairs in this task, while previous studies suggest that it is not until around 21-months that any taxonomic interference priming effect is found in children (Arias-Trejo & Plunkett, 2013). Our finding of such effects earlier in development may be due to the increased power in our analyses due to the within-subjects manipulation of age (as part of our longitudinal design) and may tap into subtle interference effects early in development. We note here, that the target items presented at test were fully counterbalanced across participants, so it is unlikely that the direction of the effect is influenced by specific properties of the target stimulus. Indeed, the only difference between targets in related and unrelated trials is the relationship between the prime presented prior to the target (which was counterbalanced across sessions and participants, such that, for a given target the same label in some cases was a related prime and in others an unrelated prime).

Notwithstanding the direction of the semantic priming effect, we found some evidence that the strength of the effect was modulated by children's vocabulary size. Here too, we note that the effect of vocabulary size was not consistent across the two analyses reported (unlike the phonological priming analyses). The traditional analyses found no interaction between vocabulary size and the semantic priming effect, finding only a strong semantic interference effect across all ages and children of different vocabulary sizes. However, the growth curve analyses, controlling for age found that adding children's expressive vocabulary size improved model fit. This highlights one difference between the two analyses, where the ANOVA examined receptive vocabulary size (for consistency with the phonological priming analyses), while the GCA found that expressive vocabulary size rather than receptive vocabulary size improved model fit. This explanation is also consistent with findings in a recent work of word recognition in toddlers (Chow et al., 2017), suggesting that access to phonological and semantic information in children of the same age may be modulated by receptive and expressive vocabulary size, respectively, as was also the case in the current study. Thus, the GCA revealed that receptive vocabulary size was a better predictor of the strength of the phonological priming effect and expressive vocabulary size was a better predictor of the semantic priming effect. Given the striking similarity in the influence of receptive and expressive vocabulary size across different samples of children learning different languages, we suggest that vocabulary size may indeed be a reliable predictor of the processes underlying word recognition, with expressive and receptive competence contributing distinctly to these effects.

5. Conclusions

Taken together, our results support earlier findings that children between 18- to 24-months-old activate phonologically and semantically related words candidates during word recognition. Overall, this simultaneous activation of other word candidates leads to interference in word recognition in children with larger vocabularies and facilitation in children with smaller vocabularies but only when examining phonological priming. This suggests that the phonological facilitation effect may have an underlying phonological bases, with activation of the target being speeded by prior activation of the overlapping phonemes. This phonological facilitation effect may be overridden in children with larger vocabularies due to lexical level competition effects that come in with such larger vocabularies. When considering the semantic links, due to the absence of phonological overlap to support the lexical access of the target label, and despite the presence of semantic overlap, all the other lexical entries (more or less abundant) compete for the lexical access. This speaks to an important role for vocabulary size in early word recognition and their differential interactions with phonological and semantic lexical links.

Declarations of Interest: none

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References

Altvater-Mackensen N., & Mani N. (2015). Phonological features mediate object-label retrieval and word recognition in the visual world paradigm. In R. Mishra, N. Srinivasan, F. Huettig (Eds.), *Attention and vision in language processing* (pp. 23-38). doi: 10.1007/978-81-322-2443-3_2

Altvater-Mackensen, N., & Mani, N. (2013). Word-form familiarity bootstraps infant speech segmentation. *Developmental Science, 16*(6), 980–990. doi: 10.1111/desc.12071

Arias-Trejo, N., & Plunkett, K. (2009). Lexical–semantic priming effects during infancy. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 3633–3647. Retrieved from http://doi.org/10.1098/rstb.2009.0146

Arias-Trejo, N., & Plunkett, K. (2010). The effects of perceptual similarity and category membership on early word-referent identification. *Journal of Experimental Child Psychology, 105,* 63-80. doi:10.1016/j.jecp.2009.10.002

Arias-Trejo, N., & Plunkett, K. (2013). What's in a link: Associative and taxonomic priming effects in the infant lexicon. *Cognition, 128*(2), 214-227.doi: 10.1016/j.cognition.2013.03.008.

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods, 37* (3), 379-384.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software, 67*(1), 1-48. doi: 10.18637/jss.v067.i01

Bates, E., & Goodman, J. C. (1997). On the inseparability of grammar and the lexicon: Evidence from acquisition, aphasia, and real-time processing. *Language and Cognitive Processes, 12*, 507-584. Retrieved from http://dx.doi.org/10.1080/016909697386628

Becker, A. B. C., Schild, U., & Friedrich, C. K. (2014). ERPs correlates of word onset priming in infants and young children. *Developmental Cognitive Neuroscience, 9*, 44-55. doi:10.1016/j.dcn.2013.12.004

Becker, A., Schild, U., & Friedrich, C. K. (2017). Tracking independence and merging of prosodic of prosodic and phonemic processing across infancy. *Developmental Science, 21*(2), e12525. doi:10.1111/desc.12525

Bergelson, E., & Aslin, R. (2017a). Nature and origins of the lexicon in 6-mo-olds. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(49), 12916-12921.doi:10.1073/pnas.1712966114

Bergelson, E., & Aslin, R. (2017b). Semantic Specificity in One-Year-Olds' Word Comprehension. *Language Learning and Development, 12*(4), 481–501.doi: 10.1080/15475441.2017.1324308

Bergelson, E., & Swingley, D. (2012). At 6-9 months, human infants know the meanings of many common nouns. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(9), 3253-3258.doi:10.1073/pnas.1113380109

Bobb, S.C., & Mani, N. (2013). Categorizing with gender: Does implicit grammatical gender affect semantic processing in 24-month-old toddlers? *Journal of Experimental Child Psychology, 115*, 297-308. doi: 10.1016/j.jecp.2013.02.006

Bobb, S.C., Huettig, F., & Mani, N. (2016). Predicting visual information during sentence processing: toddlers activate an object´s shape before it is mentioned. *Journal of Experimental Child Psychology, 151*, 51-64. doi: 10.1016/j.jecp.2015.11.002

Borgström, K., Torkildsen, J. V. K., & Lindgren, M. (2015). Event-related potentials during word mapping to object shape predict toddlers' vocabulary size. *Frontiers in Psychology, 6*, art. no. 143. doi: 10.1111/j.1365-2869.2005.00472.x

Borovsky, A., Ellis, E. M., Evans, J. L., & Elman, J. L. (2016). Lexical leverage: Category knowledge boosts real-time novel word recognition in 2-year-olds. *Developmental Science, 19*, 918–932. doi:10.1111/desc.12343

Chow, J., Aimola Davies, A. M., & Plunkett, K. (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. doi:10.1016/j.jml.2016.08.004

Chow, J., Aimola Davies, A. M., Fuentes, L. J. & Plunkett, K. (2018). The vocabulary spurt predicts te emergence of backward semantic inhibition in 18-month-old toddlers. *Developmental Science, 22*(2). doi: 10.1111/desc.12754

Delle Luche, C., Durrant, S., Floccia, C., & Plunkett, K. (2014). Implicit meaning in 18-month-old toddlers. *Developmental Science, 17*(6), 948-955. doi: 10.1111/desc.12164

Delle Luche, C., Durrant, S., Poltrock, S., & Floccia, C. (2015). A methodological investigation of the Intermodal Preferential Looking paradigm: Methods of analyses, picture selection and data rejection criteria. *Infant Behavior and Development*, *40*, 151-172. doi:10.1016/j.infbeh.2015.05.005.

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., & Pethick, S. J. (1994). Variability in early communicative development. Monographs of The Society for Research in Child Development, 59(55). Retrieved from: http://www.jstor.org/stable/1166093

Fernald, A., Perfors, A., & Marchman, V. A. (2006). Picking Up Speed in Understanding: Speech Processing Efficiency and Vocabulary Growth Across the 2nd Year. *Developmental Psychology*, *42*, 98–116. doi:10.1037/0012-1649.42.1.98

Fernald, A., Pinto, J. P., Swingley, D., Weinberg, A., & McRoberts, G. W. (1998). Rapid gains in speed of verbal processing by infants in the 2nd year. *Psychological Science, 9*, 228-231. doi: 10.1111/1467-9280.00044

Fernald, A., Swingley, D., & Pinto, J. (2001). When half a word is enough: Infants can recognize spoken words using partial acoustic-phonetic information. *Child Development, 72*, 1003–1015. doi:10.1111/1467-8624.00331.

Friedrich, M., & Friederici, A. D. (2004). N400-like semantic incongruity effect in 19-month-olds: processing known words in picture contexts. *Journal of Cognitive Neuroscience, 16*(8), 1465–1477. doi: 10.1162/0898929042304705

Friedrich, M., & Friederici, A. D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43*, 1-12. doi: 10.1111/j.1469-8986.2006.00381.x

Friedrich, M., & Friederici, A. D. (2011). Word learning in 6-month-olds: Fast encoding–weak retention. *Journal of Cognitive Neuroscience, 23*(11), 3228–3240. doi: 10.1162/jocn_a_00002

Friedrich, M., & Friederici, A. D. (2015). The origins of word learning: Brain responses of 3-month-olds indicate their rapid association of objects and words. *Developmental Science, 20(2)*, 1–13. doi: 10.1111/desc.12357

Gaskell, M. G., & Marslen-Wilson, W. D. (2002). Representation and competition in perception of spoken words. *Cognitive Psychology,45*(2), 220-266.

Golinkoff, R., Hirsh-Pasek, K., Cauley, K., & Gordon, L. (1987). The eyes have it: Lexical and syntactic comprehension in a new paradigm. *Journal of Child Language, 14*(1), 23-45. doi:10.1017/S030500090001271X

Golinkoff, R., Ma, W., Song, L., & Hirsh-Pasek, K. (2013). Twenty-five years using the intermodal preferential looking paradigm to study language acquisition: What have we learned? *Perspectives on Psychological Science, 8*(3), 316-339.doi: 10.1177/1745691613484936

Huettig, F., & McQueen, J. M. (2007). The tug of war between phonological, semantic and shape information in language-mediated visual search. *Journal of Memory and Language, 57*(4), 460-482. doi:10.1016/j.jml.2007.02.001

Jerger, S., Tye-Murray, N., Damian, M. F. von, & Abdi, H. (2016). Phonological priming in children with hearing loss: Effect of speech mode, fidelity, and lexical status. *Ear and Hearing, 37*(6), 623-633. doi: 10.1097/AUD.0000000000000334

Johnson, E. K., McQueen, J. M., & Huettig, F. (2011). Toddlers' language-mediated visual search: They need not have the words for it. *The Quarterly Journal of Experimental Psychology, 64*(9), 1672-1682. doi: 10.1080/17470218.2011.594165

Kutas, M., & Hillyard, S. A. (1980). Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biological Psychology, 11*(2)*,* 99–116.

Mani, N., & Borovsky, A. (2017). Building a lexical network. In Gert Westermann & Nivedita Mani (Eds.) *Early Word Learning* (pp. 57-69). Psychology Press.

Mani, N., & Huettig, F. (2012). Prediction during language processing is a piece of cake – But only for skilled producers. *Journal of Experimental Psychology, 38*(4), 843-847. doi: 10.1037/a0029284

Mani, N., & Plunkett, K. (2008). Phonological priming in infancy. In *Proceedings of the 30th Annual Meeting of the Cognitive Science Society* (pp. 1273–1278). Washington, USA.

Mani, N., & Plunkett, K. (2010). In the infant's mind's ear evidence for implicit naming in 18-month-olds*. Psychological Science, 21*, 908–913. doi: 10.1177/0956797610373371

Mani, N., & Plunkett, K. (2011). Phonological priming and cohort effects in toddlers. *Cognition, 121*, 196–206. doi: 10.1016/j.cognition.2011.06.013.

Mani, N., Durrant, S., & Floccia, C. (2012). Activation of phonological and semantic codes in toddlers. *Journal of Memory and Language, 66*(4), 612-622. doi: 10.1016/j.jml.2012.03.003

Mani, N., Johnson, E., McQueen, J. M., & Huettig, F. (2013). How yellow is your banana? Toddlers´ language-mediated visual search in referent-present tasks. *Developmental Psychology, 49*(6), 1036-1044. doi: 10.1037/a0029382

Marslen-Wilson, W. D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive Psychology, 10*(1), 29–63. doi: 10.1016/0010-0285(78)90018-X

Mayor, J., & Plunkett, K. (2014). Infant word recognition: Insights from TRACE simulations. *Journal of Memory and Language, 71*, 89-123. doi: 10.1016/j.jml.2013.09.009

Melinger, A., & Weber, A. (2006). *Database of Noun Associations for German*. Retrieved from: http://www.psycholing.es.uni-tuebingen.de/nag/index.php

Mills, D. L., Coffey-Corina, S. A., & Neville, H. J. (1997). Language comprehension and cerebral specialization from 13–20 months [(Special issue on origins of language disorders)]. In D. Thal & J. Reilly (Eds.) Developmental Neuropsychology, 13, 397–446.

Mills, D., Prat, C., Stager, C., Zangl, R., Neville, H., & Werker, J. (2004). Language experience and the organization of brain activity to phonetically similar words: ERP evidence from 14- and 20-month olds. *Journal of Cognitive Neuroscience, 16*(8), 1452–1464. Special Issue on Developmental Cognitive Neuroscience, Charles A. Nelson (Ed).

Mirman, D. (2014). *Growth Curve Analysis and Visualization Using R*. Chapman and Hall/CRC.

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 & Language, 59*(4), 475–494. doi:10.1016/j.jml.2007.11.006

R Development Core Team. (2008). R: A language and environment for statistical computing. Retrieved from http://www.R-project.org

Rämä, P., Sirri, L., & Goyet, L. (2018). Event-related potentials associated with cognitive mechanisms underlying lexical-semantic processing in monolingual and bilingual 18-month-old children. *Journal of Neurolinguistics*, *47*, 123-130. doi: 10.1016/j.jneuroling.2018.04.012

Rämä, P., Sirri, L., & Serres, J. (2013). Development of lexical-semantic language system: N400 priming effect for spoken words in 18- and 24-month old children. *Brain and Language, 125*(1), 1–10. doi:10.1016/j.bandl.2013.01.009

Ramos-Sanchez, J., & Arias-Trejo, N. (2018). Lexical phonological networks in children with Down syndrome: an initial syllable similarity-priming task with an eye-tracking method. *Proceedings of the Annual Meeting on Phonology*. Retrieved from http://dx.doi.org/10.3765/amp.v5i0.4233

Shukla, M., White, K. S., & Aslin, R. N. (2011). Prosody guides the rapid mapping of auditory word forms onto visual objects in 6-mo-old infants. *Proceedings of the National Academy of Sciences of the United States of America, 108*, 6038–6043.

Singh, L. (2014). One world, two languages: cross-language semantic priming in bilingual toddlers. *Child Development, 85*(2), 755–766. doi: 10.1111/cdev.12133

Styles, S. J., Arias-Trejo, N., & Plunkett, K. (2008). Priming and lexical interference in infancy. Paper presented at the Annual Meeting of the Cognitive Science Society, Washington DC, 651-656. Retrieved from https://dr.ntu.edu.sg/handle/10220/24281

Styles, S., & Plunkett, K. (2009). How do infants build a semantic system? *Language and Cognition, 1*, 1-24. doi:10.1515/LANGCOG.2009.001

Styles, S., & Plunkett, K. (2011). Early links in the early lexicon: Semantically related word-pairs prime picture looking in the second year. In G. Gaskell & P. Zwitserlood, (Eds) *Lexical representation: a multidisciplinary approach* (*pp. 51-88*).Mouton de Gruyter: Berlin. DOI (Chapter): 10.1515/9783110224931.51 DOI (Book): 10.1515/9783110224931

Swingley, D., Pinto, J., & Fernald, A. (1999). Continuous processing in word recognition at 24-months. *Cognition, 71*(2), 73-108.

Szagun, G., Stumper, B., & Schramm, S.A. (2009). Fragebogen zur frühkindlichen Sprachentwicklung FRAKIS. Frankfurt am Main: Pearson Assessment.

Teickner, C., Becker, A. B. C., Schild, U., & Friedrich, C. K. (2018). Functional parallelism of detailed and rough speech processing at the end of infancy. *Infancy, 23*(3), 386–409. doi:10.1111/infa.12218

Torkildsen, J. V. K., Sannerud, T., Syversen, G., Thormodsen, R., Simonsen, H. G., Moen, I., Smith, L., & Lindgren, M. (2006). Semantic organization of basic-level words in 20-month-olds: An ERP study. *Journal of Neurolinguistics, 19*, 431-454. doi: 0.1016/j.jneuroling.2006.01.002

Torkildsen, J. V. K., Syversen, G., Simonsen, H. G., Moen, I., & Lindgren, M. (2007). Electrophysiological correlates of auditory semantic priming in 24-month-olds. *Journal of Neurolinguistics, 20*(4), 332-351. doi: 10.1016/j.jneuroling.2007.02.003.

Von Holzen, K., & Mani, N. (2012). Language nonselective lexical access in bilingual toddlers. *Journal of Experimental Child Psychology, 113*(4), 569–586. doi: 10.1016/j.jecp.2012.08.001

Von Holzen, K., & Mani, N. (2014). Bilinguals implicitly name objects in both their languages: An ERP study. *Frontiers in Psychology, DEC* (*5*), 1–12. doi: 10.3389/fpsyg.2014.01415

Von Holzen, K., Fennell, C. T., & Mani, N. (2018). The impact of cross-language phonological overlap on bilingual and monolingual toddlers´ word recognition. *Bilingualism: Language and Cognition,* 1–24. doi: 10.1017/S1366728918000597

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. doi: 10.1111/infa.12026

Appendix A

Output of the mixed effects model including Fixed Effects of Condition and Receptive Vocabulary Size for the Phonologically Related and Unrelated trials.

Fixed effects and interactions	Estimate	SE	*t*-value	*p*(>|t|)
Intercept	0.54	0.01	87.39	**.00** * * *
Linear term	0.05	0.05	0.92	.35
Quadratic term	-0.09	0.04	-2.20	**.03** *
Cubic term	-0.02	0.02	-1.27	.20
18-months-old vs. 24-months-old	-0.00	0.00	-0.72	.47
21-months-old vs. 24-months-old	0.01	0.00	2.05	**.04** *
Linear term by 18-mo vs. 24-mo	-0.04	0.04	-0.93	.35
Linear term by 21-mo vs. 24-mo	-0.01	0.02	-0.28	.78
Quadratic term by 18-mo vs. 24-mo	0.04	0.04	1.02	.31
Quadratic term by 21-mo vs. 24-mo	0.00	0.02	0.16	.87
Cubic term by 18-mo vs. 24-mo	0.04	0.03	1.54	.12
Cubic term by 21-mo vs. 24-mo	-0.01	0.02	-0.43	.66
Condition (Unrelated vs. Related trials)	-0.02	0.01	-2.80	**.00****
Linear term by Condition	-0.08	0.05	-1.63	.10
Quadratic term by Condition	0.07	0.03	2.22	**.03***
Cubic term by Condition	0.08	0.02	4.29	**.00*****
Receptive Vocabulary	-0.00	0.00	-0.63	.52
Linear term by Rec.Voc.	0.04	0.04	0.10	.32
Quadratic term by Rec.Voc.	0.13	0.04	3.36	**.00*****
Cubic term by Rec.Voc.	0.00	0.02	0.25	.80

18-mo vs. 24-mo by Condition	0.00	0.00	0.52	.60
21-mo vs. 24-mo by Condition	0.00	0.00	0.99	.32
Linear term by 18-mo vs. 24-mo by Condition	0.01	0.04	0.33	.74
Linear term by 21-mo vs. 24-mo by Condition	0.01	0.02	0.66	.51
Quadratic term by 18-mo vs. 24-mo by Condition	-0.09	0.03	-2.52	**.01***
Quadratic term by 21-mo vs. 24-mo by Condition	-0.09	0.02	-3.97	**.00*****
Cubic term by 18-mo vs. 24-mo by Condition	-0.16	0.03	-5.99	**.00*****
Cubic term by 21-mo vs. 24-mo by Condition	-0.03	0.02	-1.27	.20
Condition by Receptive Vocabulary	0.02	0.00	3.65	**.00*****
Linear term by Condition by Rec.Voc.	-0.02	0.04	-0.38	.70
Quadratic term by Condition by Rec.Voc.	-0.12	0.03	-3.67	**.00*****
Cubic term by Condition by Rec.Voc.	-0.07	0.02	-3.30	**.00*****
18-mo vs. 24-mo by Rec.Voc.	0.00	0.00	0.28	.78
21-mo vs. 24-mo by Rec.Voc.	-0.02	0.00	-5.17	**.00*****
Linear term by 18-mo vs. 24-mo by Rec.Voc.	-0.14	0.03	-4.88	**.00*****
Linear term by 21-mo vs. 24-mo by Rec.Voc.	0.02	0.03	0.70	.48
Quadratic term by 18-mo vs. 24-mo by Rec.Voc.	-0.02	0.03	-0.70	.48
Quadratic term by 21-mo vs. 24-mo by Rec.Voc.	0.08	0.03	2.77	**.00****
Cubic term by 18-mo vs. 24-mo by Rec.Voc.	0.03	0.02	1.26	.21
Cubic term by 21-mo vs. 24-mo by Rec.Voc.	0.03	0.03	1.28	.20
18-mo vs. 24-mo by Condition by Rec.Voc.	-0.03	0.00	-6.31	**.00*****
21-mo vs. 24-mo by Condition by Rec.Voc.	0.03	0.00	6.86	**.00*****
Linear term by 18-mo vs. 24-mo by Condition by Rec.Voc.	-0.06	0.03	-2.09	**.04***

Linear term by 21-mo vs. 24-mo by Condition by Rec.Voc.	-0.09	0.03	-3.42	**.00***
Quadratic term by 18-mo vs. 24-mo by Condition by Rec.Voc.	0.18	0.03	6.60	**.00***
Quadratic term by 21-mo vs. 24-mo by Condition by Rec.Voc.	-0.11	0.03	-4.17	**.00***
Cubic by term 18-mo vs. 24-mo by Condition by Rec.Voc.	0.10	0.02	3.86	**.00***
Cubic by term by 21-mo vs. 24-mo by Condition by Rec.Voc.	0.11	0.03	4.09	**.00***

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix B

Output of the mixed effects model including Fixed Effect of Condition for children with Lower and Higher Receptive Vocabulary Size for the Phonologically Related and Unrelated trials.

Rec. Voc. Group	Fixed effects and interactions	Estimate	SE	*t*-value	*p*(>|t|)
Lower	Intercept	0.53	0.01	66.84	**0.00*** **
	Linear term	0.12	0.07	1.76	0.08
	Quadratic term	-0.09	0.05	-1.82	0.07
	Cubic term	-0.05	0.02	-2.84	**0.00** **
	Condition (Unrelated vs. Related trials)	-0.02	0.01	-2.27	**0.02***
	Linear term by Condition	-0.06	0.07	-0.85	0.39
	Quadratic term by Condition	0.03	0.04	0.68	0.50
	Cubic term by Condition	0.01	0.02	0.46	0.65
Higher	Intercept	0.55	0.01	52.62	**0.00*** **
	Linear term	0.12	0.08	1.49	0.14
	Quadratic term	-0.10	0.05	-2.02	**0.04***
	Cubic term	-0.05	0.02	-2.98	**0.00** **
	Condition (Unrelated vs. Related trials)	0.00	0.01	0.01	0.99
	Linear term by Condition	-0.03	0.08	-0.35	0.73
	Quadratic term by Condition	-0.04	0.05	-0.83	0.41
	Cubic term by Condition	-0.01	0.02	-0.51	0.61

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix C

Output of the mixed effects model including Fixed Effects of Condition and Receptive Vocabulary Size for each Session for the Phonologically Related and Unrelated trials.

Age	Fixed effects and interactions	Estimate	SE	*t*-value	*p*(>|t|)
18-months-old	Intercept	0.54	0.02	29.35	**0.00*** **
	Linear term	-0.02	0.15	-0.15	0.88
	Quadratic term	-0.15	0.11	-1.41	0.16
	Cubic term	0.02	0.03	0.59	0.55
	Condition (Unrelated vs. Related trials)	-0.01	0.02	-0.64	0.52
	Linear term by Condition	0.04	0.14	0.26	0.80
	Quadratic term by Condition	0.01	0.11	0.08	0.94
	Cubic term by Condition	-0.09	0.03	-2.99	**0.00** **
	Receptive Vocabulary	0.01	0.01	0.59	0.56
	Linear term by Rec.Voc.	-0.12	0.12	-1.05	0.29
	Quadratic term by Rec.Voc.	-0.01	0.09	-0.12	0.90
	Cubic term by Rec.Voc.	0.04	0.02	1.84	0.07
	Condition by Receptive Vocabulary	0.00	0.01	-0.28	0.78
	Linear term by Condition by Rec.Voc.	0.05	0.11	0.41	0.68
	Quadratic term by Condition by Rec.Voc.	0.08	0.09	0.86	0.39
	Cubic term by Condition by Rec.Voc.	0.03	0.02	1.40	0.16
21-months-old	Intercept	0.54	0.01	64.96	**0.00*** **
	Linear term	0.04	0.09	0.51	0.61
	Quadratic term	-0.07	0.05	-1.37	0.17
	Cubic term	-0.03	0.02	-2.25	**0.02***

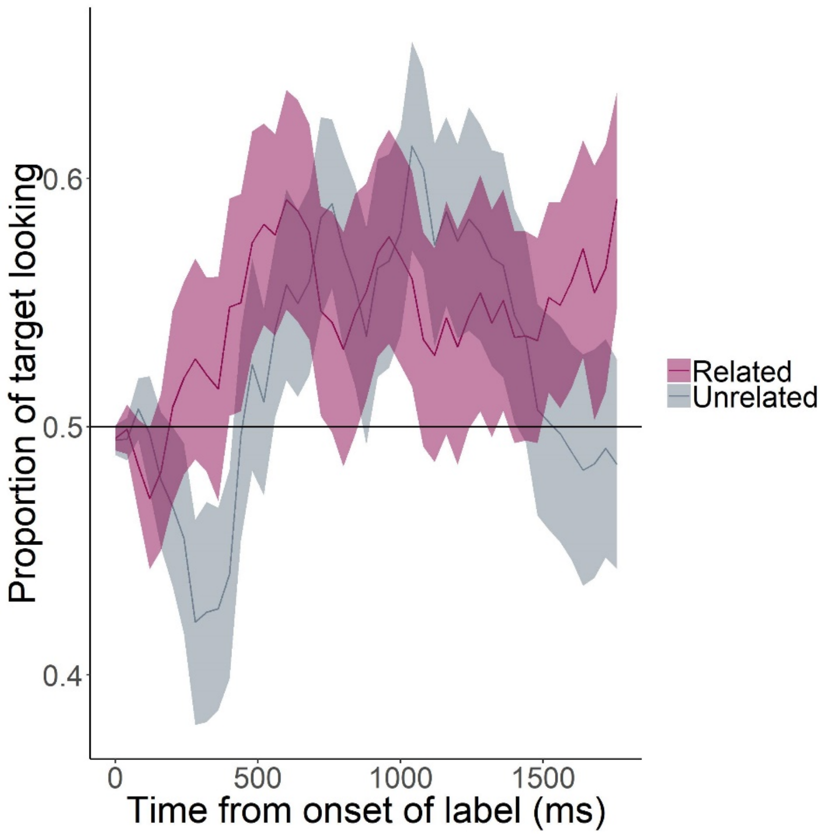
21-months-old	Condition (Unrelated vs. Related trials)	-0.01	0.01	-1.57	0.12
	Linear term by Condition	-0.08	0.08	-1.01	0.31
	Quadratic term by Condition	-0.03	0.05	-0.57	0.57
	Cubic term by Condition	0.05	0.02	3.46	**0.00*****
	Receptive Vocabulary	-0.02	0.01	-1.37	0.17
	Linear term by Rec.Voc.	0.02	0.13	0.19	0.85
	Quadratic term by Rec.Voc.	0.11	0.08	1.42	0.15
	Cubic term by Rec.Voc.	0.04	0.02	1.81	0.07
	Condition by Receptive Vocabulary	0.04	0.01	3.68	**0.00*****
	Linear term by Condition by Rec.Voc.	0.03	0.12	0.21	0.83
	Quadratic term by Condition by Rec.Voc.	-0.18	0.07	-2.63	**0.01****
	Cubic term by Condition by Rec.Voc.	0.05	0.02	2.08	**0.04***
24-months-old	Intercept	0.52	0.02	29.24	**0.00*****
	Linear term	0.13	0.13	1.01	0.31
	Quadratic term	-0.04	0.12	-0.33	0.74
	Cubic term	-0.06	0.03	-2.04	**0.04***
	Condition (Unrelated vs. Related trials)	-0.02	0.02	-1.44	0.15
	Linear term by Condition	-0.25	0.12	-2.00	**0.05***
	Quadratic term by Condition	0.23	0.10	2.24	**0.03***
	Cubic term by Condition	0.28	0.03	10.21	**0.00*****
	Receptive Vocabulary	0.03	0.02	1.55	0.12
	Linear term by Rec.Voc.	0.12	0.13	0.95	0.34
	Quadratic term by Rec.Voc.	-0.05	0.12	-0.37	0.71
	Cubic term by Rec.Voc.	-0.06	0.03	-2.27	**0.02***
	Condition by Receptive Vocabulary	0.02	0.02	1.12	0.26

24-months-old	Linear term by Condition by Rec.Voc.	0.30	0.13	2.36	**0.02***
	Quadratic term by Condition by Rec.Voc.	-0.15	0.11	-1.38	0.17
	Cubic term by Condition by Rec.Voc.	-0.28	0.03	-9.88	**0.00*****

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix D

Figure of target fixations in phonologically related and unrelated trials at 18-months-old.



Appendix E

Output of the mixed effects model including Fixed Effects of Condition and Expressive Vocabulary Size for the Semantic Related and Unrelated trials.

Fixed effects and interactions	Estimate	SE	t-value	p(>|t|)
Intercept	0.52	0.01	63.93	**.00*** **
Linear term	0.45	0.07	6.48	**.00*** **
Quadratic term	-0.06	0.05	-1.25	.21
Cubic term	-0.21	0.02	-8.06	**.00*** **
18-months-old vs. 24-months-old	-0.02	0.01	-2.72	**.01** **
21-months-old vs. 24-months-old	0.02	0.00	3.83	**.00*** **
Linear term by 18-mo vs. 24-mo	0.50	0.07	7.32	**.00*** **
Linear term by 21-mo vs. 24-mo	-0.27	0.03	-8.27	**.00*** **
Quadratic term by 18-mo vs. 24-mo	0.36	0.06	5.99	**.00*** **
Quadratic term by 21-mo vs. 24-mo	-0.22	0.03	-6.90	**.00*** **
Cubic term by 18-mo vs. 24-mo	-0.18	0.05	-3.84	**.00*** **
Cubic term by 21-mo vs. 24-mo	0.14	0.03	4.61	**.00*** **
Condition (Unrelated vs. Related trials)	0.01	0.01	1.70	.09
Linear term by Condition	-0.10	0.06	-1.72	.08
Quadratic term by Condition	-0.06	0.04	-1.37	.17
Cubic term by Condition	0.03	0.02	1.21	.23
Expressive Vocabulary	-0.02	0.01	-2.53	**.01* **
Linear term by Exp.Voc.	0.33	0.06	5.80	**.00*** **
Quadratic term by Exp.Voc.	0.21	0.05	4.51	**.00*** **
Cubic term by Exp.Voc.	-0.10	0.03	-3.43	**.00*** **

18-mo vs. 24-mo by Condition	0.03	0.01	3.73	**.00*** **
21-mo vs. 24-mo by Condition	-0.00	0.00	-0.23	.82
Linear term by 18-mo vs. 24-mo by Condition	-0.25	0.07	-3.80	**.00*** **
Linear term by 21-mo vs. 24-mo by Condition	0.16	0.03	4.81	**.00*** **
Quadratic term by 18-mo vs. 24-mo by Condition	-0.11	0.06	-1.86	.06
Quadratic term by 21-mo vs. 24-mo by Condition	0.02	0.03	0.44	.66
Cubic term by 18-mo vs. 24-mo by Condition	0.06	0.05	1.21	.22
Cubic term by 21-mo vs. 24-mo by Condition	-0.07	0.03	-2.25	**.02* **
Condition by Expressive Vocabulary	0.02	0.01	2.62	**.01** **
Linear term by Condition by Exp.Voc.	-0.30	0.05	-5.47	**.00*** **
Quadratic term by Condition by Exp.Voc.	-0.11	0.04	-2.42	**.01* **
Cubic term by Condition by Exp.Voc.	0.07	0.03	2.24	**.02* **
18-mo vs. 24-mo by Exp.Voc.	-0.05	0.01	-5.16	**.00*** **
21-mo vs. 24-mo by Exp.Voc.	0.02	0.00	3.42	**.00*** **
Linear term by 18-mo vs. 24-mo by Exp.Voc.	0.69	0.07	10.18	**.00*** **
Linear term by 21-mo vs. 24-mo by Exp.Voc.	-0.28	0.04	-7.23	**.00*** **
Quadratic term by 18-mo vs. 24-mo by Exp.Voc.	0.52	0.06	8.35	**.00*** **
Quadratic term by 21-mo vs. 24-mo by Exp.Voc.	-0.25	0.04	-6.69	**.00*** **
Cubic term by 18-mo vs. 24-mo by Exp.Voc.	-0.18	0.05	-3.27	**.00** **
Cubic term by 21-mo vs. 24-mo by Exp.Voc.	0.02	0.03	0.62	.53
18-mo vs. 24-mo by Condition by Exp.Voc.	0.01	0.01	0.92	.36
21-mo vs. 24-mo by Condition by Exp.Voc.	-0.01	0.00	-2.85	**.00** **
Linear term by 18-mo vs. 24-mo by Condition by Exp.Voc.	-0.23	0.07	-3.43	**.00*** **

Linear term by 21-mo vs. 24-mo by Condition by Exp.Voc.	-0.05	0.04	-1.30	.19
Quadratic term by 18-mo vs. 24-mo by Condition by Exp.Voc.	-0.07	0.06	-1.11	.26
Quadratic term by 21-mo vs. 24-mo by Condition by Exp.Voc.	0.07	0.04	1.99	**.05***
Cubic by term 18-mo vs. 24-mo by Condition by Exp.Voc.	0.05	0.05	1.02	.30
Cubic by term by 21-mo vs. 24-mo by Condition by Exp.Voc.	0.05	0.03	1.57	.12

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix F

Output of the mixed effects model including Fixed Effect of Condition for children with Lower and Higher Expressive Vocabulary Size for the Semantic Related and Unrelated trials.

Exp. Voc. Group	Fixed effects and interactions	Estimate	SE	*t*-value	*p*(>|t|)
Lower	Intercept	0.56	0.01	46.55	**0.00*****
	Linear term	0.21	0.09	2.35	**0.02***
	Quadratic term	-0.27	0.05	-5.38	**0.00*****
	Cubic term	-0.11	0.02	-5.51	**0.00*****
	Condition (Unrelated vs. Related trials)	0.01	0.01	1.01	0.31
	Linear term by Condition	0.13	0.08	1.66	0.10
	Quadratic term by Condition	-0.01	0.05	-0.24	0.81
	Cubic term by Condition	-0.03	0.02	-1.58	0.11
Higher	Intercept	0.54	0.01	53.34	**0.00*****
	Linear term	0.13	0.08	1.70	0.09
	Quadratic term	-0.30	0.07	-4.40	**0.00*****
	Cubic term	-0.13	0.02	-6.40	**0.00*****
	Condition (Unrelated vs. Related trials)	0.02	0.01	2.42	**0.02***
	Linear term by Condition	-0.03	0.08	-0.38	0.70
	Quadratic term by Condition	-0.10	0.06	-1.65	0.10
	Cubic term by Condition	0.00	0.02	-0.10	0.92

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix G

Output of the mixed effects model including Fixed Effects of Condition and Expressive Vocabulary Size for each Session for the Semantic Related and Unrelated trials.

Age	Fixed effects and interactions	Estimate	SE	*t*-value	*p*(>|t|)
18-months-old	Intercept	0.48	0.04	13.25	**0.00*****
	Linear term	0.37	0.35	1.06	0.29
	Quadratic term	0.27	0.20	1.33	0.18
	Cubic term	-0.49	0.06	-8.52	**0.00*****
	Condition (Unrelated vs. Related trials)	0.04	0.04	1.15	0.25
	Linear term by Condition	0.18	0.32	0.55	0.58
	Quadratic term by Condition	0.09	0.20	0.47	0.64
	Cubic term by Condition	0.15	0.06	2.64	**0.01****
	Expressive Vocabulary	-0.08	0.04	-1.89	0.06
	Linear term by Exp.Voc.	0.37	0.42	0.89	0.37
	Quadratic term by Exp.Voc.	0.70	0.24	2.93	**0.00****
	Cubic term by Exp.Voc.	-0.39	0.07	-5.79	**0.00*****
	Condition by Expressive Vocabulary	0.01	0.04	0.28	0.78
	Linear term by Condition by Exp.Voc.	0.09	0.38	0.23	0.82
	Quadratic term by Condition by Exp.Voc.	0.13	0.24	0.54	0.59
	Cubic term by Condition by Exp.Voc.	0.20	0.07	2.89	**0.00****
21-months-old	Intercept	0.54	0.01	47.42	**0.00*****
	Linear term	0.18	0.09	1.93	0.05
	Quadratic term	-0.28	0.06	-4.46	**0.00*****
	Cubic term	-0.07	0.02	-4.12	**0.00*****

21-months-old	Condition (Unrelated vs. Related trials)	0.01	0.01	1.04	0.30
	Linear term by Condition	0.06	0.09	0.67	0.50
	Quadratic term by Condition	-0.03	0.06	-0.48	0.63
	Cubic term by Condition	-0.04	0.02	-2.19	**0.03***
	Expressive Vocabulary	-0.01	0.02	-0.55	0.58
	Linear term by Exp.Voc.	-0.02	0.12	-0.13	0.89
	Quadratic term by Exp.Voc.	-0.01	0.08	-0.13	0.90
	Cubic term by Exp.Voc.	-0.08	0.02	-3.57	**0.00*****
	Condition by Expressive Vocabulary	-0.01	0.02	-0.87	0.38
	Linear term by Condition by Exp.Voc.	-0.23	0.12	-1.87	0.06
	Quadratic term by Condition by Exp.Voc.	0.03	0.08	0.35	0.72
	Cubic term by Condition by Exp.Voc.	0.12	0.02	5.42	**0.00*****
24-months-old	Intercept	0.53	0.01	36.61	**0.00*****
	Linear term	0.23	0.11	2.06	**0.04***
	Quadratic term	-0.21	0.08	-2.81	**0.01****
	Cubic term	-0.17	0.02	-8.28	**0.00*****
	Condition (Unrelated vs. Related trials)	-0.01	0.01	-0.77	0.44
	Linear term by Condition	-0.08	0.11	-0.74	0.46
	Quadratic term by Condition	-0.01	0.07	-0.19	0.85
	Cubic term by Condition	0.04	0.02	2.08	**0.04***
	Expressive Vocabulary	0.01	0.01	0.55	0.58
	Linear term by Exp.Voc.	-0.10	0.09	-1.12	0.26
	Quadratic term by Exp.Voc.	-0.04	0.06	-0.69	0.49
	Cubic term by Exp.Voc.	0.05	0.02	3.50	**0.00*****
	Condition by Expressive Vocabulary	0.02	0.01	1.58	0.11

24-months-old	Linear term by Condition by Exp.Voc.	0.06	0.08	0.77	0.44
	Quadratic term by Condition by Exp.Voc.	-0.06	0.05	-1.09	0.27
	Cubic term by Condition by Exp.Voc.	-0.04	0.02	-2.85	**0.00****

Signif. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Appendix H

Correlations between the Phonological and Semantic link at the intercept, linear and quadratic temporal terms.

Temporal term	*r*	*p*
Intercept	0.11	.52
Linear	0.09	.60
Quadratic	0.07	.67

Correlations between the Phonological and Semantic link at the intercept, linear and quadratic temporal terms at 18-, 21- and 24-months.

Temporal term	Age in months	*r*	*p*
Intercept	18-	0.19	.25
	21-	0.28	.09
	24-	0.15	.36
Linear	18-	-0.07	.84
	21-	-0.08	.62
	24-	-0.03	.84
Quadratic	18-	-0.28	.09
	21-	0.09	.58
	24-	0.28	.08

Correlations within the Phonological and Semantic links across sessions.

Lexical link	Temporal term	Age in months	*r*	*p*
Phonological	Intercept	18 and 21	0. 10	.55
		21 and 24	-0.24	.15
		18 and 24	0.07	.69
	Linear	18 and 21	0.30	.07
		21 and 24	-0.17	.32
		18 and 24	-0.12	.48
	Quadratic	18 and 21	-0.30	.07
		21 and 24	-0.32	.05
		18 and 24	0.05	.75
Semantic	Intercept	18 and 21	-0.02	.90
		21 and 24	-0.15	.36
		18 and 24	-0.15	.37
	Linear	18 and 21	-0.13	.42
		21 and 24	-0.23	.17
		18 and 24	0.11	.50
	Quadratic	18 and 21	-0.07	.67
		21 and 24	-0.18	.29
		18 and 24	-0.09	.57