Lexical-semantic system organization in the monolingual and bilingual developing brain

Louah Sirri

Ecole Doctorale 261
Comportement, Cognition, Conduites Humaines

L'organisation du système lexico-sémantique dans le cerveau monolingue et bilingue en développement

Lexical-semantic system organization in the monolingual and bilingual developing brain

Thèse de Doctorat, Psychologie Cognitive

Louah Sirri
Directrice de Thèse : Pia Rämä

Laboratoire Psychologie de la Perception
CNRS-UMR 8242

Date de soutenance Vendredi 13 Mars, 2015

Membres de Jury :

Nivedita Mani	Rapporteur
Eugenio Parise	Rapporteur
Pierre Hallé	Examinateur
Sylvain Moutier	Examinateur
Pia Rämä	Directrice de thèse

Abstract

The present doctoral research explored the developing lexical-semantic system in monolingual and bilingual toddlers. The question of *how* and *when* word meanings are first related to each other and become integrated into an interconnected semantic system was investigated. Three studies were conducted with monolingual French learning children which aimed at exploring how words are organized, that is, according to taxonomic relationships (e.g., pig – horse) and to semantic similarity distances between words (e.g., cow – sheep *versus* cow – deer), and whether cognitive mechanisms, such as automatic activation and controlled processes, underlie priming effects. An additional two studies conducted with children learning two languages simultaneously, aimed at determining, first, whether taxonomically related word meanings, in each of the two languages, are processed in a similar manner. The second goal was to explore whether words presented in one language activate words in another language, and vice versa. In an attempt to answer these questions, lexical-semantic processing was explored by two techniques: eye-tracking and event-related potentials (ERPs) techniques. Both techniques provide high temporal resolution measures of word processing but differ in terms of responses. Eye-movement measurements (Study III) reflect looking preferences in response to spoken words and their time-course, whereas ERPs reflect implicit brain responses and their activity patterns (Study I, II, IV, and V).

Study I and II revealed that words are taxonomically organized at 18 and 24-month-olds. Both automatic and controlled processes were shown to be involved in word processing during language development (Study II). Study III revealed that at 24-month-olds, categorical and feature overlap between items underpin the developing lexical-semantic system. That is, lexical-items in each semantic category are organized according to graded similarity distances. Productive vocabulary skills influenced word recognition and were related to underlying cognitive mechanisms.

Study IV revealed no differences in terms of semantic processing in the bilinguals' two languages, but the ERP distribution across the scalp varied according to the language being processed. Study V showed that words presented in one language activate their semantic representations in the second language and the other way around. The distribution of the ERPs depended, however, on the direction of translation. The results suggest that even early dual language experience yields distinct neural resources underlying lexical-semantic processing in the dominant and non-dominant languages during language acquisition.

Résumé

L'objectif de cette thèse est d'étudier le développement du système lexico-sémantique chez les enfants monolingues et bilingues. La question posée est la suivante : *quand* et *comment* les significations des mots commencent à être reliées entre elles et à s'intégrer dans un système sémantique interconnecté. Dans un premier temps, trois études ont été menées chez des enfants monolingues français. L'Etude 1, a pour but d'observer si les mots sont organisés selon des liens taxonomiques (e.g., cochon – cheval). L'Etude 2 explore si l'effet d'amorçage sémantique est sous-tendu par des mécanismes cognitifs, comme les processus d'activation automatique et contrôlé. Puis enfin, l'Etude 3 observe si les mots sont organisés en fonction de leur distance de similarité sémantique (e.g., vache – mouton *versus* vache – cerf). Dans un deuxième temps, deux études ont été conduites chez des enfants apprenant deux langues simultanément. L'Etude 4 vise à déterminer si les mots sont taxonomiquement liés dans chacune des langues. L'Etude 5 explore si les mots présentés dans une langue activent leurs représentations sémantiques dans l'autre langue. Dans le but de répondre à ces questions, le traitement lexico-sémantique a été étudié en utilisant deux techniques : l'*eye-tracking* et les potentiels évoqués (PEs). Ces deux techniques enregistrent lors de la présentation des mots des réponses comportementales (Etude 3) et neuronales (Etude 1, 2, 4 et 5) de haute résolution temporelle.

Les Etudes 1 et 2 montrent que chez les monolingues les mots sont liés taxonomiquement à l'âge de 18 et 24 mois. Durant le développement du langage, les deux processus d'activation automatique et contrôlé sont impliqués dans le traitement des mots (Etude 2). L'Etude 3 montre qu'à 24 mois, les mots sont organisés dans le système lexico-sémantique en développement selon la distance des similarités sémantiques.

L'Etude 4 montre que chez les enfants bilingues, le traitement sémantique ne diffère pas selon les deux langues, mais la topographie des PEs varie selon la langue traitée. L'Etude 5 montre que les mots présentés dans une langue activent leurs représentations sémantiques dans la deuxième langue et vice versa. Toutefois, la topographie des PEs est modulée selon la direction de traduction. Ces résultats suggèrent que l'acquisition de deux langues, bien qu'elle soit très précoce, requière deux ressources neuronales bien distinctes, sous-tendant ainsi le traitement lexico-sémantique des langues dominante et non-dominante.

Table of content

General Introduction

Even before they are capable of producing their first words, infants demonstrate a considerable understanding of basic-level word meanings by matching correctly a spoken word to its visual referent. As infants attain about 50 to 100 words in their productive lexicon, they enter the ‘vocabulary spurt’, a phase marked by an accelerate rate of word learning and producing, thus becoming faster and more efficient in recognizing familiar words (for a review, see Nazzi & Bertoncini, 2003 and Ganger & Brent, 2004). Several studies have shown that by their second birthday, children progress rapidly towards adult-like manner of word processing (e.g., Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Fernald, Swingley, & Pinto, 2001; Fernald, Perfors, & Marchman, 2006). Yet, whether their lexicon is structured according to semantic relationships between words and whether this organization affects on-line word processing is a question that has not been raised until recently. Answering this question would provide further information about the ***how*** and ***when*** during language development words relate to each other based on their shared meanings and are integrated into an interconnected semantic system. With adults, the lexical-semantic system has been investigated in numerous studies and few models of word processing have been proposed, illustrating that in the long-term memory, lexical items are organized according to different semantic relationships, such as associative, taxonomic, thematic, functional, and shared features. This semantic organization is suggested to affect word recognition during language processing. Hence, exploring the lexical-semantic organization during language acquisition will allow us to tap into the (progressive) development of the semantic system.

In monolingual children, there is recent evidence that by the second year of life associative (e.g., cat – dog) and taxonomic (e.g., cat – horse) relationships might underpin the developing lexical-semantic structure (Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007; Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2009, 2010, 2013). Still, many questions remain under-determined and further studies are needed to better understand how and when the lexical-semantic system develops. Does sensitivity to taxonomic relatedness in children appear prior to their second birthday? If yes, are automatic activation and controlled processes involved in word processing? At 24-months of age, is the lexicon organized according to another semantic relationship than taxonomic? Yet, even less is known about the developing lexical-semantic system in bilingual children acquiring simultaneously two languages from birth. How related word meanings are processed in each of the bilingual's languages and do words in one language activate their equivalent representations in the other language?

The present doctoral research was motivated by these questions with an overall objective of achieving an insight to the developing lexical-semantic system in typically developing monolingual and bilingual children. In the current studies, electrophysiological and eye-movement measurements were chosen as techniques for they provide a precise time course of responses to spoken word processing. These techniques have proved suitable for young children and do not require overt motor behavioral response, such as pointing out or producing words. Two linguistic groups were recruited for our studies, 18- and 24-month-old French monolingual learning children and 2 to 4 years old bilingual children, learning simultaneously two languages from birth (French and Spanish or French and English).

The first two chapters of this dissertation detail a general overview about the lexical-semantic organization, word processing and its underlying mechanisms in monolingual subjects, both in adults (Chapter I) and in toddlers (Chapter II), thus providing the theoretical background for our endeavor. The succeeding two chapters present a review about dual language acquisition, semantic processing and language activation in bilingual subjects, adults (chapter III) and toddlers (chapter IV). The following two chapters include our experimental studies, three conducted with monolingual children (chapter V; Study I, II, and III) and two with bilingual children (chapter VI; Study IV and V). Finally, the present dissertation concludes with a general discussion and perspectives for future studies.

Study I (**published article**) aimed at determining whether words are taxonomically linked to each other at 18- and 24-months of age and whether productive vocabulary skills contribute to this organization. The results showed that at 24-months, semantic priming effect was reflected by more negative amplitudes of the N400 ERP (known to occur in response to semantic violations) for unrelated (e.g., chicken – bike) than for related (e.g., train – bike) spoken word pairs. The N400 component was distributed over the right posterior recording sites and the effect was reversed over the frontal recording sites. Similar effects were observed in the 18-month-olds group, but only in those children with high productive vocabulary skills, suggesting that expressive skills contribute to the taxonomic organization. Study II (**published article**) explored further the semantic relatedness at 18-months of age and yielded sensitivity to taxonomic relationships at this age already. Language-related ERPs (N2 and LPN, but not the N400) were modulated in terms of amplitudes, distribution, and lateralization, by the time interval separating the onsets of the prime and target words. The results suggest that automatic activation and controlled processes are engaged during semantic priming, but that the neural mechanisms involved might be different. Study III (**article in preparation**) investigated whether at 24-months, the simultaneous presence of a visual competitor, sharing different amount of features with the target, interfered with the target word recognition, in a looking while listening task. Children viewed two images on a visual display - a named target and a semantic competitor – illustrating either concepts that were near (e.g., cow – sheep) or distant (e.g., cow – deer) competitors from the same taxonomic category, or unrelated concepts drawn from different taxonomic categories (e.g., cow – fork), while their eye-movements were being measured. The results showed that the likelihood of fixating the competitor was affected by the degree of its semantic feature similarity to the target, with distant competitor interfering less near competitor, suggesting that semantic similarity affects word recognition in a graded manner.

Study IV (**in preparation**) investigated the within-language semantic priming in French-Spanish bilingual children, who were exposed to word pairs in French (e.g., chien (dog) – âne (donkey) *versus* ventre (tummy) – âne (donkey)) and their translations in Spanish. The results showed a symmetrical N400 priming effect, but its hemispheric distribution varied according to the language. The N400 effect was left-lateralized for the dominant (French) and right-lateralized for the non-dominant (Spanish) language. Study V (**article in revision**) explored cross-language translation priming in French-English bilingual children, in attempt to determine whether words in one language activate their translation equivalents in the other language. Children were presented with prime and target words in two experimental conditions. In the forward translation, primes were in the dominant (French; e.g., ours) and targets in the non-dominant (English; e.g., bear) language. On the contrary, in the backward translation, primes were in the non-dominant and targets in the dominant language. The N400 effect occurred over the left posterior recording sites for forward translation and over the frontal recording sites for backward translation. The results revealed that the N400 priming effect was more prominent for translation equivalents than for unrelated target words. Additionally, the ERP distribution varied according to the direction of translation (posteriorly distributed effect for forward translation *versus* frontally distributed effect for backward translation). The differences between the dominant and non-dominant languages found in both studies, in terms of ERPs distribution and lateralization, indicate that distinct neural resources might underlie the lexical-semantic processing in each language.

Theoretical Background

1. Chapter I: Semantic memory and word processing

Semantics, in linguistics, is the study of relationships between signs or symbols. That is, the link between words and their meanings, the way we interpret and mentally represent them. It can be applied to entire sentences, concepts, or to single words. Understanding word meanings is essential for it allows us to understand the world, our surrounding, and thus, ourselves. The last decades have been marked with a striking increase of studies that aimed at investigating how word meanings are related to each other in our memory and form a lexicon, and the way they are processed. That is, when reading or hearing speech, what kind of representations do we construct and how they are linked to each others? Organizing words and their meanings helps structuring a single lexical network, called 'lexical-semantic system', a system that can be based on different relationships, such as associative (when one word follows another very frequently; e.g., needle – thread), taxonomic (same category co-ordinates but not associated; e.g., bread – cake), thematic (refers to an event schema; e.g., tulip – vase), functional (e.g., knife – scissors), or perceptual (e.g., snake – rope). Words can be also defined as similar in meaning according to their features overlap (e.g., categorical membership, perceptual, functional), thereby creating an organization based on similarity distances. For instance, *tomato* and *strawberry* are closely related and share more features (e.g., both are fruits, have the same colour and shape) compared to *tomato* and *potato* (e.g., a fruit *versus* a vegetable, less similar perceptually).

1.1. How to tap into the lexical-semantic organization?

1.1.1. On-line word recognition

1.1.1.1. Lexical and semantic decision tasks

To tap into the semantic system organization, 'on-line' word processing was tested in Meyer and Schvaneveldt's (1971) pioneering study, by using for the first time a primed lexical decision task. In their lexical decision task, participants were presented with prime-target word pairs and were to decide whether the target is a word or a non-word. Reaction times were measured in order to investigate how quickly participants recognize words. The results showed that participants responded faster and more accurately to target words (e.g., *butter*) preceded by associatively related primes (e.g., *bread*) compared to target words preceded by a semantically unrelated primes (e.g., *doctor*). This was defined as the "semantic priming effect", demonstrating that if information has been accessed, the time to retrieve its related information from memory is accelerated. The authors hypothesized that in the semantic memory, two associated words are located closer to each other compared to two unassociated words, thereby being rapidly accessed and their retrieval is facilitated.

Since, semantic priming paradigms have been adopted in a considerable number of studies that aimed at determining the basic lexical-semantic structure and exploring the nature of semantic relationships between words (e.g., associative and/or taxonomic, semantic similarities). Because Meyer & Scvaneveldt (1971) used only associates (considered as basic relations between lexical items) to investigate word processing, studies that followed tried to include other potential semantic relationships to provide deeper information about words organization and their retrieval (e.g., for an extensive review, see Neely, 1991). In few studies, semantic priming occurred only for associates but not for words that were taxonomically related (e.g., Shelton & Martin, 1992), while others found priming effects for both associatively (e.g., arm – leg) and taxonomically (e.g., bread – cake) related word pairs (e.g., Fischler, 1977; Neely, 1977; Seidenberg, Waters, Sanders, & Langer, 1984), suggesting that both relations, taxonomic and associative, underpin the semantic structure. However, semantic priming was shown to be sensitive also to the degree of semantic similarity between words. In lexical decision (e.g., word *versus* non-word) and semantic decision (indicate whether a word is concrete or abstract) tasks, reaction times were shown to be faster for taxonomically related and perceptually similar word pairs (e.g., jar – bottle; e.g., McRae & Boisvert, 1998; Cree, McRae, & McNorgan, 1999), compared to less similar word pairs (e.g., plate – bottle; Cree et al., 1999), for which priming effects were not significant (McRae & Boisvert, 1998). In a further study, faster reaction times were obtained for highly similar (e.g., horse – donkey) than for less similar (e.g., bear – donkey) and unrelated (e.g., thimble – donkey) word pairs. Also, reaction times were faster for less similar than for unrelated word pairs (Sanchez-Casas, Ferré, Garcia-Albea, & Guasch, 2006). These findings suggest that priming effects occur in the absence of associative relations and that similarity distance is an organizing principle of word meanings in the semantic memory (e.g., Vigliocco, Vinson, Lewis, & Garrett, 2004).

<u>1.1.1.2. Eye-movement measurements</u>

Recently, semantic processing has been also measured by using eye-tracking technique to investigate the relationship between eye-movements and word recognition, in order to provide another aspect to the semantic structure. This approach has allowed studies to analyse the time course of 'on-line' word comprehension (e.g., McRae & Boisvert, 1998; Cree et al., 1999).

The idea of using eye-tracking is to explore further what has been hypothesized by Cooper (1974): "*When people are simultaneously presented with spoken language and a visual field containing elements semantically related to the informative items of speech, they tend to spontaneously direct their line of sight to those elements which are most closely related to the meaning of the language currently heard*". Accordingly, the aim of using cross-modal paradigm was to determine whether the presence of relevant and simultaneous non-linguistic information (e.g., image illustrating an object), sharing different amount of features with the target influences subject's processing of spoken words. In accordance with the featural model (Smith, Shoben, & Rips, 1974), the meaning of a word is based upon a set of semantic features (Vigliocco et al., 2004). Words are considered as semantically similar if they share many features. Thus, the membership to a semantic category is determined by the number of shared features between items belonging to that same category. As items become more abstract, the number of their defining features decreases. The similarity effect is reflected by stronger activation of words with high amount of shared features compared to a weaker activation of words with lower amount of shared features.

Cooper (1974) demonstrated that upon hearing the word "Africa", participants were more likely to look at images illustrating semantically related members, such as lion, zebra or a snake, than other images illustrating semantically unrelated objects. Based upon these results and advancements in the eye-tracking technology, researchers have developed the visual world paradigm (VWP) to measure eye movements and their latencies in response to a spoken word (for a review, see Huettig, Rommers, & Meyer, 2011). Typically, in a VWP, participants hear a spoken word while looking at a visual display containing several objects and they are instructed to click or point out on the target object. If one of the objects (e.g., lock) illustrated in the display is semantically related to the spoken target word (e.g., key), participants tend to look longer the related (e.g., lock) than the unrelated (e.g., deer or apple) objects (Huettig & Altmann, 2004, 2005;

Yee & Sedivy, 2006; Yee, Overton, & Thompson-Schill, 2009). When the competitor images were presented simultaneously with the target image (e.g., cake) and illustrated either near (e.g., pie), distant (e.g. pear) or unrelated (e.g., stone) concepts, looking times to the competitors reflected a graded semantic competition. That is, fixations to near neighbors were greater than to distant and unrelated and fixations to distant neighbors were greater than to unrelated concepts (e.g., Huettig & Altmann, 2005; Mirman & Magnuson, 2009). These findings suggest that the likelihood of fixating a competitor object is predicted by the amount of feature similarities shared with the target concept, demonstrating that semantic system is organized by semantic similarity rather than by categorical relations (Mirman & Magnuson, 2008, 2009).

1.2. Theories interpreting semantic processing

Different theories were suggested to describe the underlying mechanisms of priming and word retrieval from memory depending on the semantic relationships. For example, associative and similarity relatedness are thought to be driven by automatic spreading activation (Collins & Loftus, 1975), compound-cue (Ratcliff & McKoon, 1988), and distributed memory (Masson, 1991, 1995) models. According to the automatic spreading activation model, nodes (words) are linked in a lexical network according to their shared meanings and are hierarchically organized. The strength of their links is not equal among words (Quillian, 1962), meaning that two concepts sharing many properties in common become closely related. As a word is processed, activation spreads through the network and other closely related words are activated, thereby facilitating their access. Hearing or reading, for example, the word '*dog*' will rapidly activate the node '*cat*'. This process is effortless, fast acting, occurs without awareness (Quillian, 1962; Collins & Loftus, 1975), and is strategy independent (Posner & Snyder, 1975; Neely, 1977; Shiffrin & Schneider, 1977). This theory assumes that weak priming effects might be due to bigger distance between two nodes. The compound-cue model assumes also that when a word is processed, its associates are also activated. But, these two models, spreading activation and compound-cue differ in terms of retrieval. In the former, activation of a word spreads from the representation of that word to other nearby word in long-term memory whereas in the latter activation occurs in short-term memory, since words are joint together into compounds and are passively matched. On the other hand, the distributed memory model presumes that activation spreads between features rather than between words (the nodes), meaning that words with features overlap are activated. The time to recognize a target word preceded by a semantically related prime is short because of the high probability that their shared features (prime and target words) were activated in the semantic system.

On the contrary, controlled processes, including expectancy and semantic matching, are characterized as slow acting and high demanding in terms of attentional capacity (e.g., Posner & Snyder, 1975; Becker 1976; Neely, 1977, 1991). The expectancy occurs when participants extract the semantic information provided by the prime to generate expectancies for potential target words. Their reaction time to target words depends on the size of the expectancy set. When the expectancy set is small (e.g., black-white), reaction times are reduced, whereas for large expectancy set (e.g., fish-shrimp) the reaction times are slowed. The semantic matching is a process that occurs when participants use the relationships between prime and target words to guide their lexical decision. After the semantic representations of the prime and target have been activated but even before the lexical decision is completed, participants match the semantic relatedness between the prime and target words. Controlled processes are the result of attentional mechanisms, and reflect post-lexical integration of a spoken or a written word into a meaning representation.

1.3. Cognitive mechanisms underlying the semantic priming

It has been suggested that priming effects might be driven by automatic activation and/or controlled processes. Several studies have attempted to dissociate these processes by manipulating either the proportion of related word pairs or the stimulus onset asynchrony (SOA; the time between the onset of the prime and the onset of the target word). Yet, the question of which process is more engaged during priming is still under debate. It has been shown that decreasing the proportion of related pairs or the SOA length (e.g., < 400 ms) within an experimental block would involve the automatic spreading activation process (e.g., Becker, 1980; Neely & Keefe, 1989; Neely, Keefe, & Ross, 1989; Seidenberg et al., 1984; Hutchison, Neely, & Johnson, 2001; Bodner & Masson, 2003). Nevertheless, it has been argued that the automatic activation produces facilitatory effects only when both prime and target words are associatively related or share many features, since results have shown that when prime and target words are associatively unrelated, reaction times are slowed due to inhibition process (for a review, see Neely 1991). Thus, automatic activation process may occur under specific circumstances: when experimental block lists contain low proportion of related word pairs and when words are associatively related (e.g., Shelton & Martin, 1992). Conversely, increasing the relatedness proportion or the SOA (e.g., > 400 ms) would increase the engagement of controlled processes. In other words, when participants are exposed to more related pairs, they are tempted to direct their attention to the semantically related words. However, it has been shown that relatedness proportion effects are eliminated when the SOA is lower than 300 ms (e.g., Stolz & Neely, 1995; Perea & Rosa, 2002), whereas in other studies, the relatedness proportion effect was shown at a SOA lower than 100 ms (e.g., Bodner & Masson, 2001, 2003), suggesting that priming effects are not influence by the subject's strategies.

These findings suggest that in the low proportion condition, any strategic responses are eliminated and automatic processes are engaged, while in the high proportion condition controlled processes are involved. In the latter condition, participants became aware of the relatedness between word pairs and oriented intentionally their attention to the semantically related target words. Other studies, in which the SOA length was manipulated, have also shown that reaction times are faster at a short than long SOA, where prime and target words occur consecutively or overlap (Neely, 1977; De Groot, 1984), suggesting that priming effect reflects automatic process. At a long SOA automatic processes decay over an extended time interval, and controlled processes are activated (e.g., Tweedy, Lapinski, & Schvaneveldt, 1977; Neely, 1977; den Heyer, Briand, & Dannenbring, 1983; Seidenberg et al., 1984; Neely & Keefe, 1989; Neely, et al., 1989) to allow deeper semantic processing of word meaning occurs when more time is allowed.

1.4. Event-related potentials (ERPs) and language processing

Language processing has been also studied by measuring event-related potentials (ERPs) in response to a complex cognitive event, such as auditory or visual linguistic stimuli. ERPs are extracted from a continuous electroencephalogram (EEG) recording, which is a non-invasive neurophysiological technique and measures the voltage fluctuations resulting from neural current flows. Since ERPs cannot be recognized on a raw EEG recording, they are extracted by averaging over a very large number of stimuli from the same stimulus category. ERPs reflect modulations of the electrical activity in response to an external event and are 'time-locked' to event. ERP measurements provide high temporal resolution that allows monitoring millisecond by millisecond the cognitive processes. They are characterized for their polarity (negative (N) *versus* positive (P)), amplitudes, onset, peak latency, and topography (distribution across the scalp). The scalp distribution is of importance because its variation demonstrates the differences in spatial configuration of the neural activity. Aside from their precise time scale, ERPs afford insight to implicit responses without any external behaviour (McCarthy & Wood, 1985; for reviews, see Osterhout, McLaughlin & Bersick 1997 and Bressler & Ding, 2006). ERP characteristics were also shown to be sensitive to the type of referencing chosen, average-reference or linked mastoids that might modulate the distribution of the component of interest, and its amplitudes (for a review, see DeBoer, Scott, & Nelson, 2007).

Several ERP components (amongst others that will not be mentioned here), have been associated with gradual stages of word processing (Fig. 1). For instance, it has been shown that N1 and P2 components are the first to appear and are sensitive to physical variations of a given stimulus (e.g., volume, frequency, intensity, duration, and phonetic changes). The auditory mismatch negativity (MMN), occurring between 150 – 250 ms post-stimulus, is an automatic and pre-attentive response to a stimulus that physically deviates from previously presented stimuli (for a review, see Näätänen, Paavilainen, Rinne, & Alho, 2007). The P3 component typically peaks between 300 and 400 ms in response to ‘oddball’ stimuli (low frequency stimuli) that are embedded in standards (non-target stimuli). That is, the P3 is associated with the detection and evaluation of deviant stimuli and reflects subjective probability of predicting the stimuli (e.g., for a review, see Nieuwenhuis, Aston-Jones, & Cohen, 2005). The N400 component is modulated by the semantic relationship between the target word and the previously presented information (for a review, see Kutas & Federmeier, 2011) whereas the P600 (late positive shift) component is modulated by the syntactic anomalies (for a review, see Kaan, Harris, Gibson, & Holcomb, 2000).

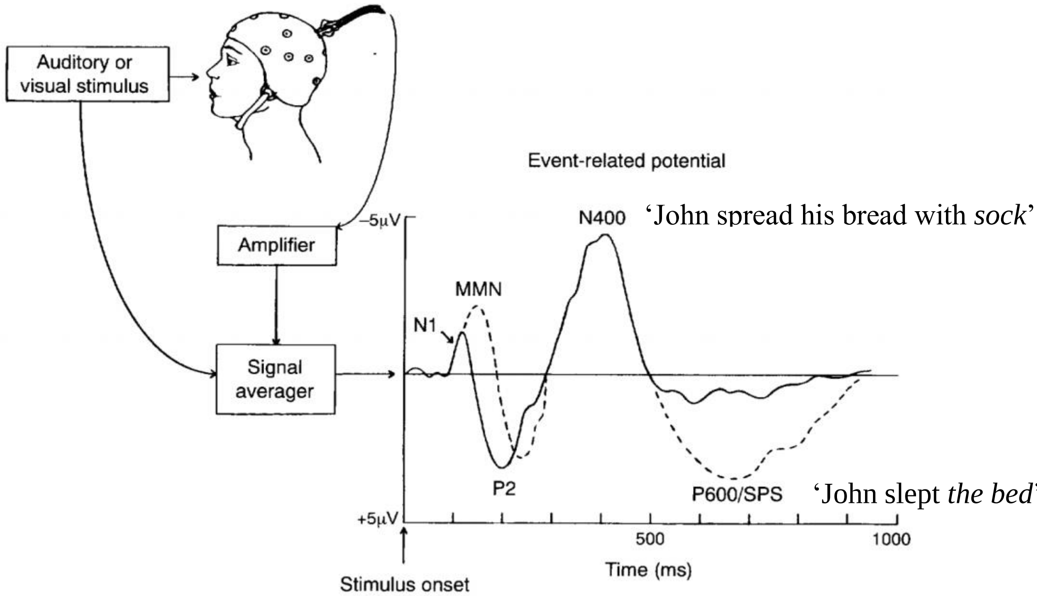


Figure 1. An illustration of obtaining event-related potentials, adapted from Osterhout et al., 1997. ERPs are extracted from the EEG by averaging across numerous presentations of visual or auditory stimuli. The N1-P2 complex occurs in response to the physical features of the stimuli. The MMN is elicited by the presentation of physically deviant stimuli. The N400 and P600 components are elicited when other aspects of words are processed, such as semantic and syntactic. While the amplitudes of the N400 are modulated by the semantic relationship between the target word (e.g., sock) and its preceding semantic context (e.g., John spread his bread with…), the amplitudes of the late positive shift (P600) are influenced by syntactically anomalous words (e.g., John slept *the bed*).

1.4.1. Semantic processing as measured by the N400

Here, the N400 component is in the main focus, for it reflects semantic processing of words. In Kutas and Hillyard's (1980) study, participants read sentences that ended either with a congruent (e.g., *I shaved off my mustache and 'beard'*) or with an incongruent word (e.g., *I take coffee with cream and 'dog'*). The discovery was a negative component that peaked around 400 ms post stimulus, namely, the N400, and was more negative for incongruent compared to congruent terminal words, revealing an incongruency effect (Kutas & Hillyard, 1980; for a review, see Kutas & Federmeier, 2000). The N400 amplitudes were also shown to be more negative to single target words (e.g., nurse) preceded by unrelated (e.g., bread) than by related (e.g., doctor) prime words. This is called the N400 priming effect. Since, numerous studies have shown that N400 amplitudes are evoked in response to any semantic violations and reflect the meaningful/non-meaningful dimension of both linguistic and non-linguistic (e.g., drawings, pictures, faces) stimuli (Federmeier & Kutas, 1999; for an extensive review, see Kutas & Federmeier, 2011).

Typically, the N400 appears over the centro-parietal recording sites (at the posterior areas of the scalp; Bentin, McCarthy, & Wood, 1985), but its latency (the time between the stimulus and the occurrence of the N400) and distribution vary according to the modality of the stimulus presentation. In the auditory modality, as opposed to the visual modality, the negativity occurs earlier, last longer, and symmetrically distributed over the left and right hemispheres (e.g., Holcomb & Neville, 1990; Bentin et al., 1985; Kutas, Van Petten, & Besson, 1988; Van Petten & Luka, 2006). These findings demonstrate that the N400 priming effect represents how related-meanings are represented in the semantic memory and that it is modality sensitive rather than modality specific.

1.4.2 Modulations of the N400

Both automatic activation and controlled processes were shown to modulate the N400 priming effects (e.g., Holcomb, 1988; Balota, Black, & Cheney, 1992; Brown & Hagoort, 1993; Anderson & Holcomb, 1995; Chwilla, Brown, & Haggort, 1995; Deacon, Uhm, Ritter, Hewitt, & Dynowska, 1999; Silva-Pereyra, Harmony, Villanueva, et al.,1999; Brown, Hagoort, & Chwilla, 2000; Hill, Strube, Roesch-Ely, & Weisbrod, 2002; Hill, Ott, & Weisbrod, 2005). There is some evidence that automatic process underlines the N400 and that controlled processes modulate its amplitudes, with larger priming effect. The N400 was shown to be more pronounced in the high than in the low relatedness proportion lists, suggesting that even if automatic processes are involved in the N400 priming effect, controlled processes contribute to its magnitude (e.g., Holcomb, 1988; Chwilla et al., 1995; Brown et al., 2000). On the other hand, Silva-Pereyra et al. (1999) found that relatedness proportion did not modulate the amplitudes of the N400, suggesting that in both conditions controlled rather than automatic processes underline the N400 effect.

While few authors suggest that automatic processes do not decay at a long SOA, such as two seconds (e.g., Deacon et al., 1999, 2000), others showed that controlled mechanisms underline the N400 priming at both short and long SOAs (Brown & Hagoort, 1993; Anderson & Holcomb, 1995; Hill et al., 2002). Anderson and Holcomb (1995) found N400 priming effects in both short and long SOAs in the visual modality but in the auditory modality priming effects were larger at the long SOA.

1.5. Conclusion

All in all, the above-mentioned studies indicate that associative, semantic feature similarities and taxonomic relationships underpin the adults' semantic structure. This structure was shown to affect word processing, but the involvement of cognitive mechanisms occurs under specific circumstances, such as, the nature of relationship between items, the proportion of related word pairs in the experiment and the length of time separating the prime and the target, thereby modulating the semantic priming magnitudes. Furthermore, the organization according to semantic similarity distances was shown to affect word recognition when it is presented simultaneously with a visual competitor reflecting thus activation in the semantic network of neighbour words sharing different amount of features.

Despite these controversies found in some studies, sufficient knowledge about shared meanings between words and their integration into an interconnected semantic network has been evidenced. Yet, whether constructing a lexicon organized by semantic relatedness is a gradual process that occurs during infancy remains unclear. There is little evidence that children are sensitive to thematic, associative and taxonomic relationships. Still, *how* and *when* during language acquisition the semantic system is developed remains under-investigated.

2. Chapter II: The developing semantic system

‘How word meanings relate to each other in the lexicon during language acquisition?’

‘When do young children start to build their lexical-semantic system?’

2.1. Vocabulary development

A few months after their first birthday, infants express a dramatic improvement in their vocabulary skills, with the capacity of learning up to ten new words per day that occurs without any formal training and independently of the speaker and context variability. This accelerated rate of word acquisition is described as a burst in noun learning and producing, namely, the *vocabulary spurt* (Bloom, 1973; for a review, see Ganger & Brent, 2004). The vocabulary spurt has been suggested to reflect striking changes in word production especially, as infants reach 50-100 words in their productive lexicon (for a review, see Nazzi & Bertoncini, 2003). It is associated to object permanence knowledge, solved word segmentation (infants are able to pick out words from running speech), naming insight (young children understand that a word refers to an object and that every object has a name), object concepts (children begin to represent and use words learnt), and categorization (children sort objects based on category membership), which enlarge the child’s lexicon and induces a better understanding of words (e.g., Bloom & Markson, 1998; for a review, see Ganger & Brent, 2004; Fernald et al., 2006). The vocabulary spurt has been repeatedly interpreted in developmental studies as a sharp transition from a slow rate to an explosion in word learning. Indeed, watching the speed in which a child acquires new words is impressive. Even so, it has been argued that the increase of word learning is not sudden; rather, it is gradual linear increase (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; Bloom, 2001). As infants get more experienced with words, they become more efficient in extracting them from speech and understand their meanings. Moreover, a recent study have shown that even prior to their first birthday, infants relate spoken words to their visual referents, suggesting that learning word meaning occurs at early stages of language acquisition (Bergelson & Swingley, 2012).

Earlier studies investigating language development during the second year of life have focused mainly on word production (e.g., naming, pointing out) and less on word comprehension. Such studies have been considered to be biased because of the young children's behaviour. If a child refuses to respond, the comprehension of words remains undetermined. Also, a child may produce words she does not necessarily understand; thus production is based on a simple repetition of a word that has been heard. Another related issue in early production is the 'overextension' (e.g., Bloom, 1973; Clarck, 1973; Huttenlocher, 1974; Thomson & Chapman, 1977; Anglin, 1977; Rescorla, 1980). The overextension is common across children and is prototypical of early word acquisition. It is defined as the use of a single word for a range of different referents from the same category. It has been argued that overextensions occur when word meanings are not well established. Clarck (1973) and Thomson and Chapman (1977) argued that overextensions are based on perceptual similarities between referents. For example, a child who produces the word '*dog*' will use it for all four-legged animals, and a child who is learning the word '*apple*', will apply it to '*tomato*' or any other referent that is round, red and of a certain size. It can be thus inferred through the authors' observations that the relationship between comprehension and production skills is not clear. Since production seems to be biased due to the reasons cited, assessing comprehension seems to be more plausible. To do so, new methods have been developed to tap into word processing and explore how word meanings relate to each other.

2.2. Exploring language processing

Several techniques have been commonly used to enlighten these questions: intermodal preferential looking (IPL; e.g., Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987; Reznick, 1990), looking while listening procedure (LWL; e.g., for a review, see Fernald, Zang, Portillo, & Marchman, 2008), head turn preference procedure (HPP; e.g., Willits, Wojcik, Seidenberg, & Saffran, 2013; Delle Luche, Durrant, Floccia, & Plunkett, 2014) and ERP measurements (e.g., Mills, Coffey-Corina, & Neville, 1993, 1997; Mills, Plunkett, Prat, & Schafer, 2005; Friedrich & Friderici, 2004, 2005, 2010, 2011; Torkildsen et al., 2006, 2007, 2008). These techniques measure the online comprehension of speech and have proven to be well adapted to infant studies because no speech production or pointing out to images is required and they are easy to use.

During an experimental trial, in HPP, the infant is seated on his caregiver's laps, facing a green center light. The green center light blinks until the infant's attention is at the midline, then it is turned off and a red flashing light at only one of the two sides indicates the availability of an auditory stimulus. As the infant turns his head to that side, the stimulus begins to play and continues until the infant turns his head away for at least 2 seconds, indicating a loss of interest. The side on which experimental trials are delivered is randomized or counterbalanced. The preference of one stimulus upon another is indexed by the average length of the infant's total looking time to the two different kinds of auditory stimuli presented on each side (e.g., Jucszyk, Cutler, & Redanz, 1993a; Nelson, Jusczyk, Mandel, Myers, Turk, & Gerken, 1995).

In both LWL and primed IPL tasks, children look at pairs of images while listening to speech naming one of the images, and their eye-movements and looking times are monitored. Word recognition is reflected by the speed of shifting gazes from the distracter to the target, while accuracy reflects the reliability of the response (Fig. 2). For example, children hear a carrier phrase 'Where's the *baby*?' while looking at paired images illustrating a baby, the target, and a dog, the distracter. Both procedures allow investigating the precise time course of child's gaze patterns in response to the named target. Also, these procedures reveal similar sensitive temporal measures as in eye-tracking studies conducted with adults.

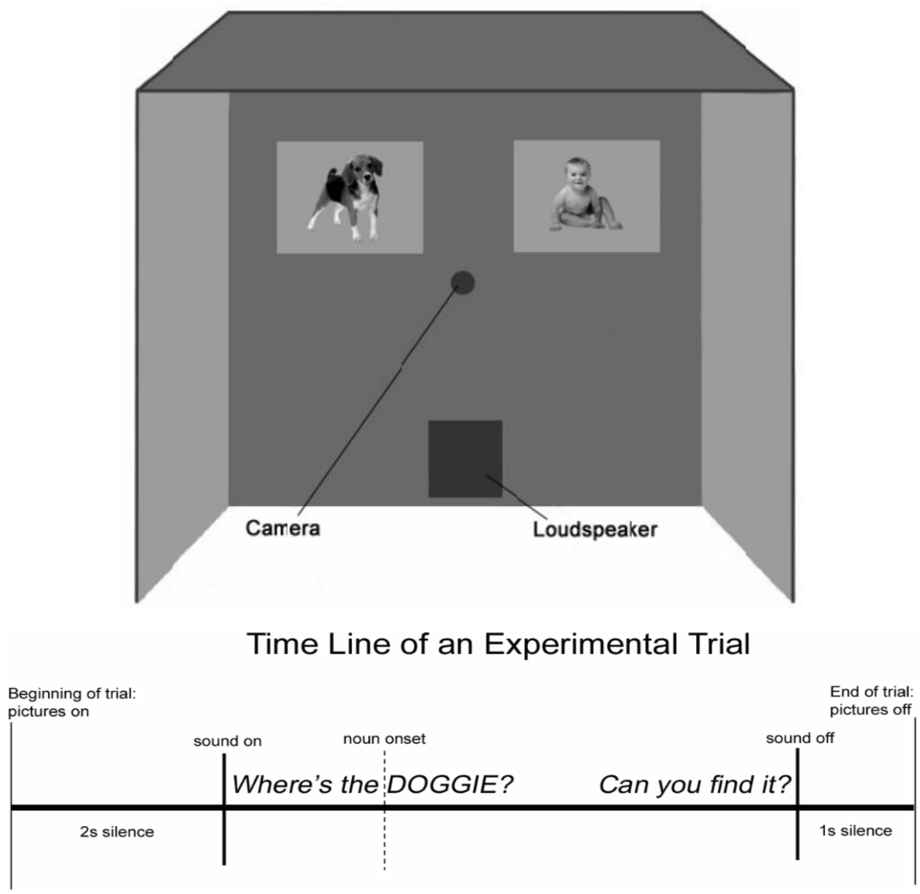


Figure 2. Configuration of a test booth and schematic time line of a typical LWL trial, adapted from Fernald et al. (2008). An experimental trial starts by presenting pairs of images for 2 seconds, during which the child explores both pictures. After 2 seconds, the sound is played and eye-movements are filmed (e.g., Where's the) and coded from the target noun onset (e.g., Doggie). On average, a trial lasts 6 to 8 seconds. The speed of reaction time in response to the named target noun is obtained from those trials where the child was looking at the distracter and then shifted to the target within the reaction time window (e.g., 300-1800 ms).

Though these behavioural procedures are easy to use with infants, some constraints are to be considered. Occasionally, it is difficult to capture the child's eye gaze for a long time because of 'fussiness' or refusal to turn the head or look at the visual display. For this reason, experiments should contain a certain amount of trials and should be limited to few minutes. It is at this point that the use of ERPs technique is the most pertinent, for it offers insight into the brain implicit responses to external auditory stimuli, such as spoken words, even when behavioural responses are not required, such as head turn or eye-movements (e.g., for reviews, see Fernald et al., 2008 and Thierry, 2005). Although obtaining considerable ERP responses requires an important amount of trials, they can be measured even during passive listening and without any visual support, affording the infant with increased mobility. Trials containing artefacts caused by eye-blinks or movements are cleaned with artefact rejection tool and are rejected in case of excessive noise. ERP measurements provide high temporal resolution, monitoring thus brain responses millisecond by millisecond. Even though some of the ERP components in young children were shown to be functionally similar to those of adults', differences exist in terms of their characteristics. In young children, ERPs are often delayed can be inverted in polarity, and their topography might vary across studies (for a review, see Thierry, 2005).

2.3. Word recognition

2.3.1. Behavioural evidence

Both accuracy and speed of familiar word recognition were shown to increase significantly over the second year, and children were shown to progress rapidly towards an adults-like pattern of language processing (e.g., Fernald et al., 1998; Swingley, Pinto, & Fernald, 1999; Fernald et al., 2001; Swingley & Fernald, 2002; Fernald et al., 2006; Hurtado, Marchman, & Fernald, 2008; Bergelson & Swingley, 2013). Children are also able to associate a familiar word to the correct image, even when presented with partial acoustic information (first 300 ms of the spoken word; Swingley, et al., 1999; Fernald et al., 2001). Moreover, efficiency in processing word is correlated with age and productive vocabulary skills of each child. Those children who are faster in shifting their gaze to the named target image have larger vocabulary. As children mature, so does their vocabulary and their ability to recognize words (e.g., Zangl, Klarman, Thal, Fernald, & Bates, 2005; Fernald et al., 2006; Hurtado et al., 2008). In other words, during early stages of language acquisition, infants recognize familiar words and as they grow older, their vocabulary is increased, thus contributing to the speed and accuracy of spoken word processing. However, a recent study showed that infants recognized familiar words even prior to their first birthday, at 6 to 9-months, suggesting that relating a basic-level word to its referent occurs at this age already. This finding indicates further that at this age, word learning in not limited to sound structure of the native language but also to some of the word meanings (Bergelson & Swingley, 2012).

2.3.2. Electrophysiological correlates of word processing

Several components (e.g., N2, N350, N400, N600-900) were found to be associated with language processing during development. It has been suggested that the *N2*, a negativity occurring at 200 ms post-stimulus reflects the adults' MMN (Thierry, Vihman, & Roberts, 2003). The N2 in 11-month-old infants was shown to be more sensitive to familiar words compared to rare (unfamiliar) words, indicating an automatic orientation of the attention to frequently heard words (Thierry, et al., 2003). The N2 was more negative over the right than over the left recording sites, assuming an early right-hemispheric involvement during language acquisition. While at 13 to 17-months, N2, N350, and N600-900 ERPs were broadly and bilaterally distributed, at 20-months, the effects were distributed over the temporal and parietal recording sites and left lateralized (Mills, Coffey-Corina, & Neville, 1993, 1997). These changes in ERPs distribution across age, from broadly distributed to more focal patterns, are suggested to reflect changes in the way lexical items are processed with increased language experience and a left hemispheric specialization for language (Mills, et al., 1993, 1997). The N600-900 component was larger for known than unknown words, over the right frontal recording sites at 13- and 17-months. The N400 priming effect in response to incongruent picture-word pairings was shown to occur in 19-month-olds and was broadly distributed (Friedrich & Friederici, 2004). In all these studies, language-related ERPs were also shown to be more pronounced in children with high comprehension skills, suggesting that receptive vocabulary contribute to the brain activity patterns.

2.4. The developing lexical-semantic system

Whether newly acquired words are semantically related to each other and integrated into an interconnected lexical-semantic system remains to be determined. It has been earlier suggested that word meanings are learnt in isolation and represented independently of each other (e.g., Anglin, 1970). For instance, young children learn and use '*cat*' and '*dog*' but they do not yet relate them to each other based on their semantic relationship. This question is of great importance because to date, the nature of semantic relations structuring the lexical memory during language acquisition, is under-determined. There is little evidence that pre- and school-aged children are sensitive to thematic, associative, and taxonomic relationships, indicating that these relationships might underpin the lexical memory structure as in adults (e.g., Schvaneveldt, Ackerman, & Semlear, 1977; McCauley, Weil, & Sperber, 1976; Nelson, 1985; Blewitt & Toppino, 1991). Moreover, it has been suggested that over childhood there is an early (up to 6 years old) preference for thematic relations (e.g., eggs – cereals: breakfast schema) that is shifted later (from 8 years old and on) into a dominant preference of taxonomic relations (e.g., ice-cream – toast) considered to be more abstract (e.g., Hashimoto, McGregor, & Graham, 2007). In line with earlier theories (e.g., Inhelder & Piaget, 1964), these findings demonstrate that the developing conceptual system is structured according to thematic relationships and only later in childhood taxonomic relationships are integrated (for a review see Lin & Murphy, 2001). However, a study by Waxman & Namy's (1997) showed that there is no preference of thematic (e.g., tiger – cage) over taxonomic (e.g., tiger – panda bear) relations, at younger ages as 4-, 3-, and even 2 years, suggesting that sensitivity to taxonomic relationships between items occurs much earlier than originally assumed (Markman & Hutchison, 1984).

2.4.1. Tackling the lexicon structure over the second year

2.4.1.1. Primed IPL tasks

It has been recently suggested that word meanings are semantically organized in a lexical-semantic system towards the second year of life (Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2009, 2013; Johnson, McQueen, & Huettig 2011). In these studies, an adaptation of the IPL procedure to priming paradigm was applied (Arias-Trejo & Plunkett, 2009, 2010, 2013; Styles & Plunkett, 2009). In the primed IPL paradigm, children hear a carrier phrase containing a prime word (e.g., "yesterday I bought a *cat*") followed by an isolated target word, either semantically related (e.g., dog) or unrelated (e.g., plate) to the prime word. A few hundred milliseconds after the spoken target word onset, a pair of images, composed of the named target and a distracter, appears on the screen (Fig. 3). The priming effect is expressed by an increased looking time at the named target when it is preceded by a semantically related as opposed to unrelated prime word.

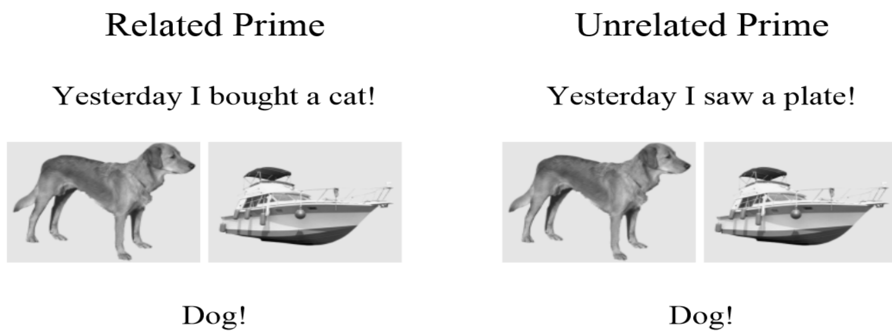


Figure 3. An illustration of a trial in a primed IPL task, adapted from Style & Plunkett's study (2009). Each trial starts with a priming phrase (e.g., *Yesterday I bought a cat*), followed by an inter-stimulus interval (ISI) of 200 ms. Then the target word is delivered in isolation (e.g., *Dog*) and the presentation of target and distracter images begins at an SOA of 200 or 400 ms from the onset of the target word. The paired pictures remain on the screen for 2500 ms. Priming effect is reflected by longer looking to the target (e.g. dog) as opposed to the distracter (e.g. boat), indicating recognition of and preference to the target word.

The results of primed IPL tasks revealed that at 24-month-old, but not younger, children were sensitive to different semantic relationships between lexical items (Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2013). Priming effects were found for taxonomically related (e.g., rabbit – horse), associatively related but drawn from different semantic categories (e.g., carrot-bunny), and for both taxonomically and associatively related (e.g., cat – dog). Furthermore, when named target was absent (e.g. monkey), 24-month-olds were more likely to look at a taxonomically related (e.g., dog) than an unrelated image (e.g., apple) (Johnson et al., 2011). At 21-months, priming effects depended on 'associative boost', that is, priming occurred only when primes and targets were both taxonomically and associatively related (e.g., cat – dog). In addition, 18-month-olds looked at the named target irrespectively of its semantic relationship to the prime. At this age, priming effects occurred under specific circumstances, that is, when the prime and target were repeated and when the target word was named. The authors suggest that 18-month-olds are sensitive to the relationships between two identical words but that word meanings are not yet related to each other. Rather, lexical items are represented as isolated 'islands' in the semantic network. These findings reveal that only 24-month-olds, but not younger, integrate words into an interconnected lexical-semantic system according to different relations suggesting that taxonomic, associative, or both relation combined underpin the semantic organization.

2.4.1.2. N400 priming effect

The N400 ERP component has been associated to semantic processing also in young children. In picture-word priming tasks, the N400 was elicited at 19-months and was more negative for incongruent (e.g., word *dog* – picture of a *car*) than for congruent (e.g., word *dog* – picture of a *dog*) matching, over the left temporal and parietal recording sites (Friedrich & Friedrici, 2004; 2005b; Torkildsen et al., 2006). When the vocabulary size was included as a factor, the N400 effect was found to be larger over the right than the left hemisphere, as in adults (Friedrich & Friedrici, 2004). Studies have shown that the N400 effect was also obtained at 14- to 24-month-olds (Friedrich & Friederici, 2004, 2005a, 2005b, 2006), but not in younger infants as 12-month-olds, demonstrating that even though the mechanisms of N400 are mature already at 6-months (Friedrich and Friedrici, 2011), lexical-semantic representations are not yet consolidated at 12-months (Friedrich & Friederici, 2010). At 14-month-olds, children are able to integrate visual and auditory information based on their semantic relationship (Friedrich & Friederici, 2004, 2005a, 2005b, 2006, 2010).

It should be noted that the previously mentioned results were interpreted as a semantic integration of relationships between words. Still, the incongruity between a picture and a spoken word does not indicate whether words are organized into superordinate categories. To date, one study investigated the lexical-semantic structure in cross-modal priming (Torkildsen, Sannerud, Syversen, Thormodsen, Simonsen, Moen, Smith, & Lindgren, 2006). At 20-month-olds, the N400-like effect was obtained in between-category (e.g., a picture of a dog with the word “car”) and within-category (e.g., a picture of a dog with the word “cat”) violations, but it was larger for between- than for within-category violations (Torkildsen et al., 2006), suggesting that children were capable of discriminating between two basic-level words from the same superordinate category.

Although these studies indicate that by the end of the second year, the N400-like response reflect semantic integration of related picture-word pairs, even less is known about processing semantically related spoken words. There are only a few studies in which language-related ERPs in response to spoken words were investigated to explore the semantic memory structure (e.g., Friedrich & Friedrici, 2005c; Silva-Pereyra, Klarman, Lin, & Kuhl, 2005; Torkildsen et al., 2007). The results indicated that N400 ERP occurred in response to spoken incongruent terminal words (Friedrich & Friedrici, 2005c) and to taxonomically unrelated spoken word pairs (Torkildsen et al., 2007), suggesting that words might be semantically organized in the developing lexicon However, further investigation is needed to clarify these findings.

2.5. Productive vocabulary skills influence on lexical-semantic processing

As discussed earlier, larger vocabulary size during the second year contributes to a better and more efficient processing of words (Zangl, Klarman, Thal, & Bates, 2001; Fernald et al., 2001, 2006). In the previously mentioned primed IPL tasks, receptive (Style & Plunkett, 2009) or receptive and productive vocabulary size (Arias-Trejo & Plunkett, 2009; Arias-Trejo & Plunkett, 2010) at all ages studied (18-, 21-, and 24-months) did not predict the magnitude of priming effects. The authors suggested that word recognition is not affected by the number of words in the child's lexicon. Rather, priming effects were correlated to the familiarity with the words used during the experiment (e.g. Arias-Trejo & Plunkett, 2010), since children were tested with words that parents reported as known.

Productive vocabulary has been shown to modulate the brain pattern activity associated with word familiarity and processing novel word-picture associations. The N200-500 component, at 20-months, was found to be associated to learning novel word and novel word – object pairs (Mills, Plunkett, Prat, & Schafer, 2005) and to the congruity violations of these new learnt mappings (Torkildsen, Svangstu, Hansen, Smith, Simonsen, Moen, & Lindgren, 2008). When associating novel words to referents, the N200-500 was broadly and symmetrically distributed (Mills et al., 2005). The more the spoken words were repeated within the novel-object pair trials, the larger the N200-500 became, revealing a process of learning the new word meanings. The magnitudes of the N200-500 effect were not modulated by the children's vocabulary skills. Still, a (non-significant) left hemispheric bias was found in high producers who have just acquired new word-object pairing (Mills et al., 2005), indicating that asymmetrical ERPs distribution emerges earlier when learning is accelerated. On the other hand, when the newly acquired picture-word associations were violated, the N200-500 effect was stronger in 20-month-old high producers than in the low producers, indicating that increased vocabulary enhances the establishment of new word meanings (Torkildsen, 2008). In the low producers group, the effect was weaker than in the high producers group and occurred later, supporting previous behavioural findings that productive skills contribute to the speed of word processing. These findings demonstrate that 20-month-olds can integrate a spoken word to its visual context and rapidly familiarize with new pairings, especially when productive skills are increased.

Furthermore, it has been shown that increased vocabulary size modulated the lateralization and the timing of the N400 ERP, with a right hemispheric bias (Friedrich & Friedrici, 2004; 2005b) and earlier effect (Torkildsen et al., 2006) in those children whose vocabulary was larger. Similarly, the N400 effect at 12-months depended on the productive skills of infants and occurred only in infants with an accelerated rate of word production (four words and more), suggesting that the neural mechanisms indexing the N400 effect might not yet be triggered by the existing lexical-semantic representations in infants with normal language development. In those 12-month-old high producers, the N400 effect yielded a right hemispheric as in 19- and 14-months and in adults (Friedrich & Friederici, 2005a, 2005b, 2008) but with longer latencies, suggesting slower semantic processing. Thus, the occurrence of the N400 priming effect might be related to a certain state of brain maturation and the strength of lexical-semantic representations (Friedrich & Friederici, 2010).

2.6. Conclusion

Altogether, the previously mentioned studies reveal that over the second year of life children become more efficient at recognizing familiar words and progress towards adult-like word processing. There is also some evidence that word meanings are associatively and/or taxonomically related to each, suggesting that these semantic relationships might underpin the developing lexical-semantic structure. Even though productive skills were shown to contribute to the speed of word processing and modulate brain pattern activity, it is still unclear whether high productive skills contribute to the developing lexical-semantic organization.

3. Chapter III: Lexical-semantic processing in bilinguals

3.1. Defining a bilingual individual

In many countries of the world, being a bilingual is a norm rather than exception. A bilingual is usually defined as an individual who uses regularly his/her two languages on a daily basis. There are bilinguals that have been exposed to both their languages from birth (simultaneous) and others who acquired their second language after the first language has been established (sequential). Balanced bilinguals are considered to be equally proficient in both of their languages (L1 = L2) while unbalanced bilinguals are more proficient in one of their languages (L1 > L2). Although this definition of bilinguals seems simple, researchers studying bilingual subjects experience a common difficulty in evaluating the 'who is bilingual?' An individual acquiring a second language may undergo many contextual changes that would potentially modulate his linguistic skills in both of his/her languages. For example, it was believed that age of acquisition is associated with higher proficiency level. This was proven to be a false assumption since bilinguals in some contexts (e.g., immigration, second language immersion) might even forget their native language, even when the second language immersion occurs as late as 8 years of age (e.g., Ventureyra, Pallier, & Yoo, 2004). Therefore, age of acquisition alone cannot count as a determinant factor. The amount of exposure, current usage, circumstances of the language use, and fluency are factors (amongst others) to be considered when studying bilinguals. However, a more recent study have shown that even when exposure to the first language has been interrupted during early childhood, its neural representations are maintained. These findings indicate that neural circuits initially established are not overwritten by those of the newly acquired language (Pierce, Klein, Chen, Delcenserie, & Genesee, 2014).

It has been suggested that bilingualism enhances cognitive control functions such as inhibitory control, switching attention, sustained attention, and working memory. Bilingual adults, even those who are unbalanced, were shown to outperform their monolingual counterparts in many non-linguistic tasks. But, when tested on verbal skills (receptive and productive) in each of their languages, bilinguals tend to be slower and less accurate than monolinguals, even if they are to answer in their dominant language. Particularly, semantic fluency tasks revealed that bilinguals also tend to have smaller vocabulary in each of their languages compared to monolinguals (for review, see Bialystok & Luk, 2012).

3.2. Bilingual lexical-semantic processing

Recently, an increased interest within the bilingual language processing aimed at determining at which level lexical and/or conceptual representations in both languages are shared or separated. Many questions have been raised, such as whether the lexical-semantic structure is organized differentially depending on the age of acquisition (AoA) or proficiency level in each of the languages and whether this organization results in (non) selective language processing. It has been suggested that AoA (e.g., before or after the age of 7 years) may not account as the only determinant factor, as proficiency level in L2 was also shown to influence the bilingual language processing. The interaction between both factors contribute to the structure of the lexical-semantic (conceptual) structure (e.g., Hahne, 2001; Silverberg & Samuel, 2004; Moreno & Kutas, 2005; Isel, Baumgaertner, Thrän, Meisel, & Büchel, 2010).

3.2.1. Within-language semantic priming

A few within-language priming studies, using lexical-decision tasks, aimed at exploring whether the N400 behaves similarly, in terms of latency, distribution or lateralization, when L1 and L2 are processed (e.g., Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Weber-Fox & Neville, 1996; Moreno & Kutas, 2005). When compared to monolinguals, bilinguals' first and second language processing was shown to be delayed, as revealed by a later peak amplitudes of the N400 priming effect. In bilinguals, the N400 effect was left lateralized for both languages, whereas in monolinguals it was right lateralized, suggesting that the neural mechanisms underlying priming effects are not identical in the two linguistic groups (Ardal et al., 1990). In another study, the N400 effect in early bilinguals (< 10 years of age) was comparable to that of monolinguals whereas in late bilinguals (> 10 years of age), the N400 peaked later with longer latencies than those of monolinguals and bilinguals, suggesting that late second language exposure slows semantic processing and that even high proficiency level cannot compensate the delay (Weber-Fox & Neville, 1996). However, Moreno & Kutas (2005) argued that AoA is not the only factor to determine the speed of processing but also proficiency and the frequency of use, since in their study, the N400 peaked later for the less dominant language, even if it was originally the L1. This result demonstrates that the shift in the dominance can occur during second language acquisition. Slower processing in L2 (lasting 400 ms longer) than in L1 was suggested to reflect longer effort of semantic integration (Hahne & Friederici, 2001). Also, speed of semantic processing in adult bilingual's second language can be attributed to two determinant factors to be considered simultaneously: Vocabulary proficiency and age of exposure (Moreno & Kutas, 2005; for a review, see Moreno, Rodriguez-Fornells, & Laine, 2008). Furthermore, it was demonstrated that in highly proficient bilinguals processing words in one language activates words in the other language that are phonologically and semantically (Hoshino & Thierry, 2011) or phonologically and orthographically (e.g., Wu & Thierry, 2010) related, demonstrating suggesting that language processing in bilinguals in non-selective. processing. Altogether, these studies demonstrate that differences between semantic processing in L1 and L2 pertain to N400 latency and lateralization but no distributional (anterior *versus* posterior) differences were found.

3.2.2. Cross-language activation

Cross-language priming paradigms (e.g., translation or semantic relatedness) have been also applied to further explore whether both languages are activated simultaneously, by measuring reaction times or by measuring the N400 effect in lexical decision tasks. In cross-language lexical-decision tasks, forward priming consists of presenting the prime in the first language acquired (L1) and the target in the second (L2) whereas in backward priming, the prime is in L2 and the target is in L1. While some studies found a symmetrical priming effect in both directions (e.g., Basnight-Brown & Altarriba, 2007; Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009 ; Dunabeitia, Perea, & Carreiras, 2010; Geyer et al., 2011; Schoonbaert et al., 2011), others did not show such effect, in terms of priming magnitudes, N400 amplitudes or timing (e.g., Gollan et al., 1997; Alvarez, Holcomb, & Grainger, 2003; Voga & Grainger, 2007; Midgley, Holcomb, & Grainger, 2009; Hoshino et al., 2010). Symmetrical priming effects indicate that primes in L1 activate the representations of target words in L2 and vice versa in a similar manner, suggesting that during word processing, lexical-semantic representations in both languages are co-activated. Greater proficiency in L2 was shown to contribute to these symmetrical priming effects and enable direct access to L2 semantic representations (e.g., Basnight-Brown et al., 2007; Dunabeitia et al., 2010). Asymmetrical priming effects, on the other hand, show that access to sematic representations occurs only in one direction, suggesting that one language may be more activated than the other.

These resulting controversies might be due to experimental manipulations (for a review, see Altarriba & Basnight-Brown, 2007). As suggested by the authors, some issues are to be considered when studying bilingual participants. For instance, if automatic and pure semantic activation is explored, then cognate (words with identical spelling, pronunciation a meaning across languages) stimuli should be excluded from the experimental paradigm and the SOA length should be similarly controlled across conditions. Also, questionnaires about linguistic background and proficiency used may have led participants to over- or under-estimate their skills in L2. Therefore, on-line measures of proficiency measures (reading, writing, speaking, and listening) might enable participants to better estimate their linguistic skills. Even though age of the second language acquisition is an important factor, the way it was acquired (e.g., only by parents *versus* formal education) and its frequency of use are to be considered as well.

3.3. Interpreting the bilingual language processing

Three models attempted at understanding the bilingual language processing and each suggested a lexical-semantic structure, based on results obtained in priming tasks. The revised hierarchical model (RHM; Kroll & Stewart, 1984) was initially developed to explain the asymmetries in priming tasks, where effects from L1 to L2 were found to be larger than L2 to L1. These asymmetries are explained by the fact that L2 is lexically connected to L1, while L1 to L2 is mediated by semantic connections. Thus, in the latter condition, the priming effect is more pronounced, since it engages more semantic mediations (for an extensive review, see Kroll et al., 2010). At initial levels of the second language acquisition, L2 words are mapped onto their L1 translations and access to lexical and conceptual representations in L2 are based on L1 linkage. As a bilingual becomes proficient, he/she can map L2 words directly to its lexicon and access the conceptual representations without the L1 mediation. It was hypothesized that only highly proficient and balanced bilinguals can access words in L2 at the same speed than those in L1 (e.g., Midgley, Holcomb, & Grainger, 2009). It means that processing is based on selective access either in L1 or in L2.

The RHM served, for three decades now, as model in cross-language semantic priming tasks to explain the asymmetrical effects. Still, the model does not provide description of the conceptual system architecture and it assumes that separate lexicons for each language result in selective access. However, it has been demonstrated that 'switching off' completely the second language seems to be impossible and that both languages are activated to some degree in proficient bilinguals (e.g., Dijkstra & van Heuven, 2002; Kroll & de Groot, 2005; van Assche Duyck, Hartsuiker, & Diependaele, 2009). Furthermore, there is increased evidence that both languages are activated even when only one is being processed in a given context (e.g., Marian & Spivey, 2003; Dijkstra, 2005; Kroll et al., 2006; Duyck, Assche, Drieghe, & Hartsuiker, 2007; Thierry & Wu, 2007). Thierry and Wu (2007) have shown that in Chinese (L1) - English (L2) bilinguals, L2 words were automatically and unconsciously translated into L1 words. Similar results were earlier found in a few VWP studies, where proficient Russian-English bilinguals participated to a word recognition task (Spivey & Marian, 1999; Marian & Spivey, 2003). Under instruction such as "Pick up the stamp" (in Russian: "Podnimi *marku*"), participants were more likely to fixate a "marker" on the display before switching to the stamp. These findings demonstrate 'non-selective' language activation in proficient bilinguals, suggesting that when processing words in a given language, the second language is activated as well and might interfere during word processing.

However, De Groot and colleagues (e.g., 1992, 1995; van Hell & De Groot, 1998) argued that the RHM does not explain how semantic features overlap between prime and target words in cross-linguistic tasks can modulate the magnitudes of priming effects. The authors proposed the distributed representational (lexical/conceptual) feature model (DRM), which assumes that semantic priming depends on the amount of shared features between L1 and L2 words, suggesting that activation of words in both languages depends on their shared features and thus, their similarity distances (Guasch, Sanchez-Casas, Ferré, & Garcia-Albea, 2011). The more words both languages share, the bigger the priming effect is. It has been demonstrated that the strength of nodes are established according to the word type, meaning that translation equivalents, concrete words and cognates are strongly linked and accessed faster compared to abstract words and non-cognates.

Unlike the RHM and the DRM, the bilingual interactive activation model (BIA) includes one single integrated lexicon for both languages (Grainger & Dijkstra, 1992; van Heuven, Dijkstra,

& Grainger, 1998). Lexical processing operates in top-down control to select the context-relevant language, meaning that bilinguals extract information from the words and make a decision whether it belongs to L1 or to L2. The word processing starts with a non-selective access and rapidly converges to the selected language. Once the decision made, only the appropriate language remains activated. The aim of the top-down selection is to prevent interferences of the second language during word recognition.

3.5. Conclusion

The findings about bilingual's semantic processing indicate that during word processing both languages are activated to a certain degree, according to the level of proficiency attained in the second language. It has been suggested that even when bilinguals are equally proficient in the two languages, their brain pattern activity is modulated by the frequency of use. These modulations are reflected in terms of priming magnitudes, N400 latency and lateralization. Distribution of the N400 priming effect was not shown to vary across studies. Even though models attempted at describing language processing and activation in bilinguals, they are lacking a developmental aspect of the semantic memory. Do bilingual children, acquiring two languages from birth, access word meanings in L1 and L2 similarly? Is processing affected by language dominance? The goal of the following chapter is to provide evidence to date about bilingual language experience during language development.

4. Chapter IV: What do we know about language processing in bilingual toddlers?

4.1. Dual language acquisition

The evaluation of the adult's bilingualism, whilst difficult, is of little comparison to that of the difficulties with evaluating a child's bilingualism. Usually, young bilinguals, or 'dual language learners', are defined as children who acquire two languages simultaneously from birth or acquire a second language at very early stages of development (e.g., before the age of 3 years). Bilingual children must face the challenge of learning a second language even when the first one is not yet fully mastered. As argued by Carlson & Meltzoff (2008), to date, an objective standard for bilingualism does not exist and for this reason, defining a child as bilingual is an important factor to be considered when studying dual language acquisition. Unlike adults, the knowledge of any language is incomplete in children; thus, the question of 'how much input in each language is enough' plays a major role in defining bilingualism during development (for a review, see Bialystok, 2001). It has been suggested that a bilingual is an individual who can function in each language according to a given context (Grosjean, 1998). Often, bilingual children are raised in unequal linguistic environment, which consists of dominant language, spoken by the majority, and non-dominant language, spoken by a minority. Also, in some cases, children are exposed to two languages but learn to speak only one (De Houwer, 2007). Therefore, the parental input used at home is of importance for it correlates with differences in the child's language use.

4.1.1. Parental language input

Recently, it was demonstrated that the pattern of each parent speaking both languages reduces the frequency of the non-dominant language input. Parental language mixing might even be detrimental to vocabulary acquisition because children express difficulties at determining which word is drawn from which language (Byers-Heinlein, 2012). In this study, high rates of parental language mixing were shown to predict slightly lower vocabulary skills during the second year. It is suggested that learning a word from a single language sentence for a bilingual child might be easier than learning words from language-mixed sentence. Therefore, the 'one parent - one language' parental input pattern, among others, is thought to be ideal for transmitting the minority language to the child. Still, even with this input pattern, bilingual children are more likely to hear less speech in each of their languages as opposed to monolinguals (e.g., for a review, see Leiven, 2011). Furthermore, it was shown that one parent - one language is neither necessary, nor sufficient for the non-dominant language to be acquired since other factors are to be considered, such as the quality and the quantity of linguistic input, parental attitude towards bilingual development, and sociocultural environment. Having older siblings can also be advantageous or disadvantageous for he/she speaks the outside language, which is the dominant one. As argued earlier, the second language acquisition is related to a 'maximal engagement' with that language. The more input the child receives, the greater she will learn it (for a review, see Yamamoto, 2001). Continual practice in the non-dominant language prevents intrusions from the dominant language (for a review, see Hernandez, Li, & MacWhinney, 2005).

4.1.2. Code-mixing during dual language acquisition

Another issue to be considered is that for long time, it was thought that bilingualism during infancy, even with little input, might induce a delay in both languages development. Parents' main concern was that their child would confuse the languages and become incompetent in both languages. It was believed that code-mixing, that is using words from two languages in the same sentence, is a sign of language confusion (e.g., Volterra & Taeschner, 1978). However, further research about bilinguals' code-mixing has demonstrated that bilingual children code-mix in order to fill a gap in the developing lexicon (for review, see Genesee, 2006), since they do not yet master each of their languages. This process is more prominent when children have to use their less dominant language, indicating that in order to express themselves, children tend to use their both linguistic resources. On the other hand, code-mixing has been shown to be context-sensitive, enabling children to use their languages according to their interlocutor (e.g., Genesee, Nicoladis, & Paradis, 1995; Genesee, Boivin, & Nicoladis, 1996). It means that children code-mix because, first, when they lack an appropriate lexical item in one language, they tend to produce it in the second language in which this item is known (Genesee, 1989); second, they understand that each interlocutor does not necessarily speak their both language, thereby, mixing languages according to a given context. Watching children code-mix might simply reflect the permanent activation of both languages during language processing. It has been also suggested that code-mixing reflects changing social relationships and identities that is, belonging to given cultural membership (for a review, see Ritchie & Bhatia, 2012).

4.1.3. Similarities and differences between mono- and bilingual infants

Similarities

An increase interest within the investigation of dual language acquisition during early stages has shown that bilingual infants achieve their language milestones within the same age as their monolingual peers (e.g., Pearson, Fernandez, & Oller, 1993; Oller, Eilers, Urbano, & Cobo-Lewis, 1997; Petitto, Katerelos, Levy, Gauna, Tétreault, & Ferraro, 2001; Kovelman, Baker, & Petitto, 2008). In both linguistic groups, *onset of canonical babbling* (Oller et al., 1997), *first word production* (Genesee, 2003; Patterson & Pearson, 2004), and *vocabulary growth* in both languages (Pearson et al., 1993, 1997), occur at the same age. When comparisons were made in speech perception tasks between monolingual and bilingual infants and between both bilinguals' languages, similarities were revealed in *phonological perception*, even when learning two rhythmical similar languages (e.g., Spanish-Catalan; e.g., Bosch & Sebastián-Gallés, 1997, 2001), and even shortly after birth in newborns of mothers who spoke two languages during pregnancy (e.g., English-Tagalog; Byers-Heinlein, Burns, & Werker, 2010). Further similarities were also found in *use of prosodic cues*, such as pitch and duration (Gervain & Werker, 2013); at *discriminating phonetic representations* in both native languages (Burns, Yoshida, Hill, & Werker, 2007), and *word segmentation* (Polka & Sundara, 2003). These findings suggest that language development is not delayed nor compromised by a second language acquisition.

Differences

Nevertheless, other studies have shown that a few differences exist between both language groups in some aspects of speech perception. Bilingual infants exhibit a delay, compared to monolinguals, in perceiving *phonetic contrasts* when learning words and are slower in constructing *phonological representations* (Fennell, Byers-Heinlein, & Werker, 2007). Although it has been shown that bilingual infants display a vocabulary growth at the same of monolinguals, it seems that bilinguals have fewer words in each of their languages (e.g., Oller, Pearson, & Cobo-Lewis, 2007; Bialystok, Luk, Peets, & Yang, 2010). Moreover, as opposed to monolinguals, bilinguals tend to show a weaker use of disambiguation (e.g., Byers- Heinlein & Werker, 2009, 2013), where they are to infer that a novel word refers to an unfamiliar object, a sign of learning the meanings of novel words (Bion, Borovsky, & Fernald, 2013).

These similarities and differences in bilingual speech perception were suggested to be correlated with the amount of time spent in each language which influences the vocabulary skills in the dominant and non-dominant languages (e.g., Pearson, Fernandez, Lewedeg, & Oller, 1997; Garcia-Sierra, Rivera-Gaxiola, Percaccio, Conboy, Romo, Klarmin, Ortiz, & Kuhl, 2011; Byers-Heinlein & Werker, 2013).

4.1.3. Bilingual experience and cognitive development

4.1.3.1. Benefits and costs

Benefits

There is increased evidence that (early) bilingualism enhances the development of executive functions (EFs). The neural mechanisms underlying the EF are centered in the prefrontal cortex. EFs are considered as crucial cognitive achievement during childhood, and continue developing until adolescence (for reviews in extension, see Bialystok & Craik, 2010 and Barac, Bialystok, Castro, & Sanchez, 2014). EFs are defined as attentional control and inhibition (ability to resist a non-relevant information), working memory (ability to maintain temporarily an information and manipulate it), and cognitive flexibility (ability to adjust to changes according to the actual context). It is still unclear how much linguistic input from each of the languages is required in order to enhance the development of EFs. It has been suggested that enhanced EFs result from early, systematic and intensive exposure to both languages. This evidence was revealed in a study where children that have been immersed in a second language environment for 6 months, exhibit same behavioral patterns as monolinguals and were not advantaged (Carlson & Meltzoff, 2008).

Recently, studies have shown a bilingual advantage in tasks involving complex cognitive behavior, in which bilinguals outperformed their monolingual counterparts (for a review, see Bialystok, Craik, & Luk, 2012), even during the first year of life (Kovacs & Mehler, 2009). This advantage during the first year of life was also shown to be extended to visual language discrimination (Weikum, Vouloumanos, Navarra, Soto-Faraco, Sebastian-Gallés, & Werker, 2007; Sebastian-Galles, Albareba-Castellot, Weikum, & Werker, 2012). In pre-school and school-aged children especially, the bilingual advantage was found in tasks including: switching rules (e.g., Kovacs & Mehler, 2009a; Okanda, Moriguchi, & Itakura, 2010), non-verbal auditory response inhibition (e.g., Foy & Mann, 2013), high demands on working memory (e.g., Morales, Calvo, & Bialystok, 2013), inhibiting interference from irrelevant stimuli (Bialystok, Craik, & Luk, 2008; Carlson & Metlzoff, 2008; Martin-Rhee & Bialystok, 2008; Bialystok & Viswanathan, 2009; Yang, Yang, & Lust, 2011), and understanding the mental representations of others and false beliefs (e.g., Bialystok & Senman, 2004). Further studies have demonstrated that this robust enhancement is related to bilingualism *per se*, due to daily exercise of language switching, and independent of cultural background, immigration history, or language of instruction (e.g., Bialystok et al., 2010; Yang et al., 2011; Barac & Bialystok, 2012).

<u>*Costs*</u>

In spite of the findings, in the above-mentioned studies, the cognitive enhancement in bilinguals was shown mostly in the non-verbal (visual) domain. Bilingual experience appears to have not only benefits but also costs. The costs are reflected by lower vocabulary rate in each of the bilingual's language and weaker access to lexical items than monolingual speaker of that language (e.g., Bialystok, 2001; for a review, see Bialystok & Craik, 2010). When studied in the verbal/auditory domain, such as naming, semantic fluency or Go-NoGo tasks, both language groups, at 5 to 6 years of age, tend to have similar results or even a disadvantage for bilinguals (e.g., Carlson & Metltzoff, 2008; Bialystok & Feng, 2011; Foy & Mann, 2013). When vocabulary skills in each of the languages (dominant and non-dominant) are evaluated separately, a deficit is observed. But, such a deficit is eliminated when both L1 and L2 words are combined (e.g., Pearson et al., 1993; Marchman, Fernald, & Hurtado, 2009; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

4.2. Word processing and lexicon structure

Despite of the increasing number of studies on dual language experience, there is still a limited evidence of how words in both languages are processed, whether newly acquired words are related to each other and organized in a (shared or separated) lexical-semantic system, and whether processing is language selective or not. Recently, the BIA model was re-described from a developmental perspective (BIA-d), in order to better understand the second language vocabulary acquisition and the lexical-semantic structure (Grainger, Midgley, Holcomb, 2010). Although the BIA-d is also based on adult findings, some aspects can be still implemented into developmental studies to clarify the above-uninvestigated questions. This model explains the L2 vocabulary acquisition after representations of the have already established (Fig. 4). When a word is learnt in L2, it is automatically translated into L1 and a semantic representation of that new word is constructed. Once the links between lexical and semantic representations in L2 are strengthened, words acquired in L2 form direct links to their semantic representations and are integrated into a shared lexical-semantic system shared. Furthermore, increased L2 vocabulary size contributes to the autonomy of that language and decreases asymmetries between both languages.

Yet, as argued, this model describes the second language acquisition in those subjects who master their L1. Young children acquiring simultaneously two languages do not master either of their languages and a large inter-individual variability exists in terms of amount of exposure, that is, the dominance in L1 or in L2. Thus, it is unclear whether one developing lexical-semantic system will be structured, inducing a co-activation of words in both languages. This question of nonselective language access was recently explored by applying phonological priming with an IPL task (Von Holzen & Mani, 2012). 31-month-old German-English bilingual toddlers exhibited an increased looking time to the named target in L1 (e.g., slide) when preceded by phonological related prime in L2 (e.g., kleid (dress)) but not when the L2 prime translation rhymed with the L1 target word (e.g., leg (bein) – stone (stein)). The results suggest that during word recognition, both languages are activated at the phonological level supporting the hypothesis of non-selective language activation (Von Holzen & Mani, 2012). Nevertheless, there is no indication whether nonselective language access occurs also at the lexical-semantic level.

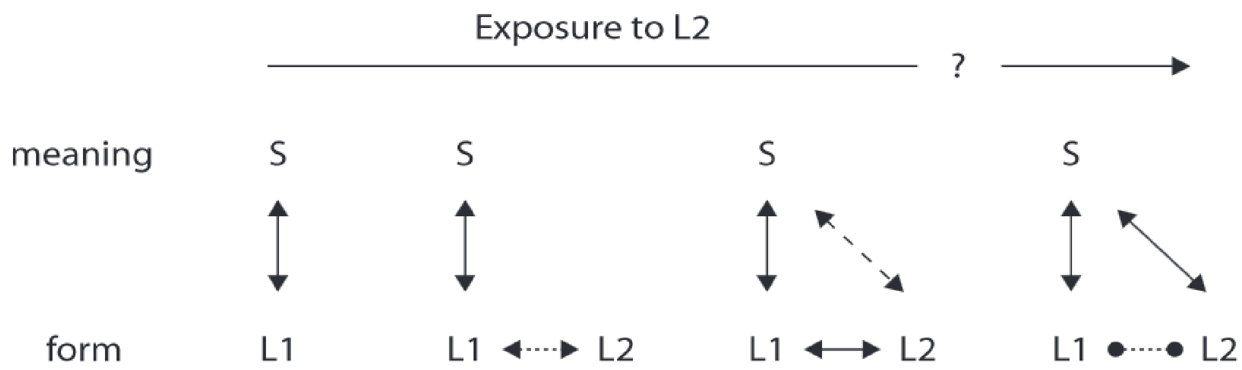


Figure 4. An illustration of the BIA-d model, adapted from Grainger et al. (2010). L1 and L2 refer to representations of word form in the first and second language. S refers to semantic representations shared by these word forms. Arrows represent excitatory connection, when L2 words are rapidly integrated into a shared lexicon. Filled circles represent inhibitory connections with both L2 and L1 words that are semantically unrelated. Full lines represent stronger connection than dotted lines, indicating direct link between L2 words and their semantic representations.

4.2.1. Semantic processing in bilingual toddlers

Despite the emergence of an increased interest in the dual language acquisition and its effects on cognitive development, very little is still known about the developing lexical-semantic system(s) of bilingual children. A few studies aimed at investigating the semantic processing in pre-school aged bilingual children. In a word-picture priming task, 2-3 year-old bilingual children were shown to pay more attention than monolinguals to incongruent pictures, as indexed by greater pupil dilation compared to congruent pictures, suggesting that semantic stimuli are processed more efficiently in bilingual toddlers (Kuipers & Thierry, 2013). In a another study, using within- and cross-language primed IPL task, the priming effects in 30-month-old bilingual children occurred only for the dominant language or when the prime was presented in the dominant and the target in the non-dominant language , suggesting that activation of both languages depends on the proficiency in each of the languages (Singh, 2014). The author further suggested that words in the dominant language might have stronger representations, thereby, being processed more efficiently than words in the non-dominant language.

Even though semantic processing remains to be explored, a few studies have demonstrated that ERP components, such as N2, N4, and N200-400, were associated to familiar word recognition in bilingual children. It was also shown that the brain pattern activity (timing, distribution) depends on the amount of language experience. In a word familiarity task with 11-month-old bilingual infants, neural processing was shown to be faster for the dominant than for the non-dominant language (Vihman, Thierry, Lum, Keren-Portnoy, & Martin, 2007). This difference was reflected by longer latencies of N2 and N4 amplitudes for the non-dominant language. Furthermore, it was suggested that not only language experience but also vocabulary size in each of the bilingual's languages, modulated the distribution of the ERPs (Conboy & Mills, 2006). The results of this study, with 19-22 month-old bilinguals, showed that the N200-400 component was larger to known as opposed to unknown words, and that increased vocabulary size in the dominant language contributes to the right lateralization of the N200-400 effect, whereas no such asymmetry was found in the non-dominant language. These findings suggest both languages are not processed by identical neural systems.

So far, the question of whether words acquired in both languages are integrated into one or two interconnected semantic systems is still unclear.

5. Conclusion

Altogether, these recent findings indicate that infants raised bilingually do not exhibit any delay in their linguistic abilities; rather, they are advantaged in many of the developing executive functions compared to their monolinguals peers. Also, a few studies revealed that language experience influences the brain activity patterns and that the degree of language co-activation depends on the experience acquired with both languages (dominant *versus* non-dominant).

The goals of our studies

The aim of the following studies is to explore how word meanings are related to each other in the developing lexical-semantic system of monolingual and bilingual toddlers. Language-related ERPs in response to spoken words were measured in Study I, II, IV and V, whereas in Study III, looking times to a named target were measured LWL task.

In Study I, the ERPs of 18- and 24-month-old children were recorded during auditory semantic priming task in order to investigate whether words are organized according to taxonomic relationships and whether the ERPs, associated to lexical-semantic processing, are modulated by the children's productive skills. In earlier primed IPL tasks, priming effects were not found at 18-months. Also, in many of the developmental studies, priming paradigms contain spoken words that are related to visual referents and even less is known about language processing in the auditory modality, when no visual support is presented. Therefore, the use of ERPs is of relevance for it provides implicit brain responses related to auditory semantic processing and its time course that might not be observable behaviorally.

Study II explored the cognitive mechanisms underlying language-related ERPs (N200, N400 and LPN) at 18-months. By manipulating the stimulus onset asynchrony (SOA), that is, the time between the onset of the prime and the onset of the target, the study investigated whether automatic activation or controlled processes contribute, during language development, to the auditory semantic processing.

In Study III, 24-month-old children were tested in a LWL paradigm to investigate whether the presence of a visual semantic competitor, sharing different amount of features, interferes with word recognition. This study aimed at exploring, first, whether words are organized according to their shared features, that is, to semantic similarity distances. Recall, two concepts are defined as highly similar or less similar based on their features overlap (e.g., taxonomic, perceptual, functional). Second, whether enhanced productive skills contribute to this refined organization.

The underlying assumptions are as follows: First, if word meanings are taxonomically organized at 18- and 24-months of age, then the N400 effect should be greater in response to taxonomically unrelated than to related target words. Second, if language-related ERPs are modulated according to the semantic relatedness and SOA length, it could be assumed that automatic activation and controlled processes are involved during word processing at 18-months of age. The occurrence of priming effects at short SOA would indicate that automatic activation process is involved, whereas modulations (in terms of magnitude and ERPs lateralization) of these effects at the long SOA would indicate that controlled processes are engaged. Finally, if the lexical-semantic system is taxonomically organized and based on features overlap between words, then highly similar items should interfere more with word recognition than less similar items, reflecting thus graded semantic organization.

In Study IV, French-Spanish bilingual children participated to an auditory within-language priming task, where words were presented in the dominant (D) or in the non-dominant (ND) language. The goal was to investigate whether priming effects occur in both languages and whether words are similarly processed in each language. Based on previous findings with bilingual adults and children, it can be hypothesized that differences between D and ND in terms of distribution and lateralization would suggest that distinct neural resources underlie the semantic processing of both languages. On the other hand, the occurrence of the N400 priming effect only for the D would demonstrate weaker lexical-semantic representations in ND.

Study V aimed at investigating whether words in the dominant language activate the corresponding semantic representations in the non-dominant language and vice versa. A symmetrical N400 priming effect (forward and backward translation) would indicate that words in one language activate their lexical-semantic representations in the other language and vice versa, suggesting that words in both languages are semantically related. On the contrary, asymmetrical priming effect and differences in terms of amplitudes, lateralization, and distribution of the N400, would demonstrate that non-identical neural resources underlie word processing in both languages.

Experimental Chapter

[Study I: Published]

Development of lexical-semantic language system: N400 priming effect for spoken words in 18- and 24-month old children

Pia Rämä[1, 2], Louah Sirri[1], and Josette Serres[1, 2]

[1] Laboratoire Psychologie de la Perception, Université Paris Descartes, Paris, France, [2] CNRS (UMR8158), Paris, France

Correspondance:

Pia Rämä

Laboratoire Psychologie de la Perception (CNRS UMR 8158)

Université Paris Descartes

45, rue des Saints-Pères, 75006 Paris, France

Email: pia.rama@parisdescartes.fr

Tel : +33 (0)1 42 86 40 65

Fax: +33 (0)1 42 86 33 22

Abstract

Our aim was to investigate whether developing language system, as measured by a priming task for spoken words, is organized by semantic categories. Event-related potentials (ERPs) were recorded during a priming task for spoken words in 18- and 24-month-old monolingual French learning children. Spoken word pairs were either semantically related (e.g., train-bike) or unrelated (e.g., chicken-bike). The results showed that the N400-like priming effect occurred in 24-month-olds over the right parietal-occipital recording sites. In 18-month-olds the effect was observed similarly to 24-month-olds only in those children with higher word production ability. The results suggest that words are categorically organized in the mental lexicon of children at the age of two years and even earlier in children with a high vocabulary.

Key words: Semantic priming, auditory modality, ERPs, N400, language development

1. Introduction

Semantic priming provides a tool to study the organization of words in semantic long-term memory (e.g., Meyer & Schvaneveldt, 1971; Kutas & Hillyard, 1989; Lucas, 2000). Behaviourally, the semantic priming effect is reflected by faster reaction times and more accurate identification of a target word (e.g., east) when it is preceded by a semantically related (e.g., west) compared with a semantically unrelated (e.g., table) prime word (e.g., Meyer & Schvaneveldt, 1971). Both automatic and attentive processes have been shown to influence the priming effect (Neely & Keefe, 1989; Neely, Keefe, & Ross 1989). Automatic processes are the automatic spreading of activation from one activated representation of a word to another in a semantic network (Collins & Loftus, 1975) whereas attentive processes are those involved in expectancy and post-lexical processing (Becker 1976; Neely, 1977).

In event-related potential (ERP) studies, a negative waveform that peaks between 350 and 550 ms post-stimulus onset (the N400 response) is more negative for unrelated than for related prime-target word pairs (e.g., Bentin, McCarthy, & Wood, 1985; Holcomb, 1988; Brown, Hagoort, & Chwilla, 2000). This is called the N400 effect. A more pronounced N400 response has also been recorded for incongruent than for congruent terminal words of sentences (e.g., Kutas & Hillyard, 1980; Federmeier and Kutas, 1999). Furthermore, it has been shown that although both within-category and between-category incongruous sentence completions elicit more pronounced N400 responses than congruous completions, the N400 response to between-category violations is larger than the N400 response to within-category violations (Federmeier and Kutas, 1999), suggesting that the N400 response reflects the influence of semantic memory structure on language processing.

The N400 effect is typically strongest over the central and parietal recording sites (e.g., Bentin et al., 1985). For written words, the effect is usually more pronounced at the right than the left recording sites (e.g., Bentin et al., 1985; Kutas, Van Petten, & Besson, 1988; Van Petten & Luka, 2006) but more symmetrically distributed for auditorily presented words (for review, see Van Petten & Luka, 2006). In a study by Holcomb and Neville (1990), the N400 effect was observed in both visual and auditory tasks, but it began earlier, was larger in amplitude, and lasted longer in the auditory modality, suggesting that priming processes in two modalities are not identical. Some studies have shown that the N400 effect is elicited even when attention is directed to other than semantic features of language (Kutas & Hillyard, 1989; Perrin & García-Larrea, 2003; Heil, Rolke, Pecchinenda, 2004; Dombrowski & Heil, 2006; Relander, Rämä, & Kujala, 2009) or to another modality (Relander et al., 2009; Rämä, Relander-Syrjänen, Carlson, Salonen, & Kujala, 2012), whereas others have not observed a significant N400 effect in an un-attended condition (Deacon, Breton, Ritter, & Vaughan, 1991; Besson, Boatz, Fischler, & Raney, 1992; Chwilla, Brown & Hagoort, 1995; Mari-Beffa, Valdes, Cullen, Catena, & Houghton, 2005).

The ERP technique has been used also in young children to investigate word comprehension and semantic processing (e.g., Thierry, Vihman, & Roberts, 2003; Mills, Coffey-Corina, & Neville, 1993; Mills et al., 1997; Mills, Plunkett, Pratt, & Schafer, 2005; Friedrich & Friederici, 2004, 2005a, b, 2006; Torkildsen et al., 2006; Torkildsen, Syversen, Simonsen, Moen, & Lindgren , 2007). Mills and co-workers (1993, 1997, 2005) studied word comprehension in 13 to 20-month-old children while presenting them with known and unknown words. The amplitudes of two ERP components, the N200 and N375, were larger to known than to unknown words, suggesting that the ERPs differ as a function of word familiarity within 200 milliseconds after the word onset (Thierry et al., 2003; Mills et al.,1993, 1997). In younger (13-17-month-old) children, these components were observed bilaterally and broadly distributed over the anterior and posterior recording sites (Mills et al., 1997), whereas in 20-month-olds, they were larger in the temporal and parietal recording sites only over the left hemisphere (Mills et al., 1993). More recently, it has been suggested that individual experience, such as exposure to bilingual input, rather than age influences the distribution of brain activity associated with word processing (Mills et al., 2005; Conboy & Mills, 2006).

Comprehension of word meaning in young children has been studied also using a picture-word matching task (Friedrich & Friedrici, 2004, 2005a, 2005b, 2006; Torkildsen et al., 2006**).** In the picture-word matching task, the participants are presented with spoken words that are either congruous or incongruous to the picture content (e.g., the word *dog* together with a picture of a *dog* or a *car*). The results showed that an incongruous picture-word pair compared with a congruous pair elicited a larger negative N400-like response over the frontal and centro-parietal recording sites. The effect was more extended over time in the left hemisphere in children in contrast to more extended activation in the right hemisphere in adults (Friedrich & Friedrici, 2004;

2005b; Torkildsen et al., 2006). However, it has been shown that in a group of children whose vocabulary size was large, the effect occurred in the right hemisphere (Friedrich & Friedrici, 2004; Torkildsen et al., 2006). In the study by Torkildsen et al. (2006), the incongruity between the picture and the word was either between-category (e.g., a picture of a dog with the word "car") or within-category (e.g., a picture of a dog with the word "cat") violation, and the ERPs were compared with those elicited by a congruent (e.g., a picture of dog with the word "dog") condition. The N400-like effect was observed in both incongruity conditions in 24-month-olds, but it was larger for between- than for within-category violations, suggesting that children were capable of discriminating between two basic-level words in the same superordinate category (Torkildsen et al., 2006). The N400-like effect has been observed in 14- to 24-month-olds, and also in 12-month-olds with a relatively high (more than 4 words) productive vocabulary, suggesting that children by the age of 12-months are capable of integrating visual and auditory information based on their semantic content (Friedrich & Friederici, 2004, 2005a, 2005b, 2006, 2010). Recently, the N400 effect was shown to appear even in 6-month-olds after few exposures of novel object-word combinations, suggesting that the mechanisms of N400 are mature already in early infancy (Friedrich and Friedrici, 2011).

However, during the picture-word matching task, the N400 effect is most probably associated with processing of incongruity between the picture and the word content, and it does not provide information about whether the language system is organized by semantic categories, unless the N400 effect for "between" and "within-category" violations are compared as Torkildsen et al. (2006) did. In addition, as indicated earlier the mechanisms of priming effect may vary according to the modality (e.g., Holcomb & Neville, 1990). To our knowledge, there are only a few ERP studies in which the effect of semantic memory structure on on-line language processing was investigated in the auditory modality in young children (e.g., Friedrich & Friedrici, 2005c; Silva Pereyra, Klarman, Lin, & Kuhl, 2005; Torkildsen et al., 2007). In the study by Torkildsen et al. (2007), the N400 effect was obtained in 24-month-old children in a semantic priming task for spoken word pairs. In another study conducted in the auditory modality, the ERPs to incongruous terminal words in a sentence were contrasted with those of congruous terminal words in 19- and 24-month-old children (Friedrich & Friedrici, 2005c). The N400 effect was obtained in both age groups, but the distribution of the effect was broader in younger children. In addition to ERP evidence, there is also behavioural evidence that 21- and 24-month olds exhibit a semantic priming effect in an “intermodal preferential looking (IPL)” paradigm (e.g., Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987; Fernald, Zangl, Portillo, & Rachman, 2008) whereas no effect was obtained in 18-month-olds (Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009). Even though behavioural and electrophysiological results have shown that infants do understand the meaning of words in a picture-word context and discriminate between familiar and unfamiliar words already at the beginning of their second year of life (or even earlier, see Friedrich & Friedrici, 2011; Bergelson & Swingley, 2012), they start to organize words by semantic relatedness in their mental lexicon later. However, in previously mentioned behavioural studies (Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009), the relation between the prime and target words was both taxonomic and associative (e.g., cat-dog), and thus, it remains unclear whether the lexicon is organized by semantic categories or by associations between word-pairs. In addition, as IPL paradigm was used in these studies, the visual component is inherent in the task. Torkildsen et al. (2007) used an auditory priming task, but unfortunately did not sufficiently control the occurrence of target words (the same words were not used for “related” and “unrelated” targets). Furthermore, in their study, the priming effect was tested only in 24-month-olds.

In our current study, we recorded ERPs during an auditory semantic priming task in young children in order to ascertain whether words in long-term semantic memory storage are organized by semantic categories in 18- and 24-month-olds, and whether this organization influences (non-attentive) processing of spoken words. The children were exposed to spoken word pairs that were either semantically related (e.g., train-bike) or unrelated (e.g., chicken-bike). Target words were the same in the related and unrelated conditions to ensure that the influence of word frequency, word familiarity, and experience with words did not differ between related and unrelated word pairs. The relation between the words was taxonomic, that is, the words belonged to the same semantic category but they were not associatively related. The number of syllables, phonemes, and the duration of words did not differ between the prime and target words. The children were sitting in front of loudspeakers, allowed to play with toys, and visual stimuli were not synchronized with the spoken word pairs. Based on previous behavioural evidence on semantic priming (Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009), we expected that the N400 priming effect would be obtained in 24-month-olds, but not yet in 18-month-olds. However, earlier evidence suggests that not only age, but also increasing familiarity with words (Mills et al., 2005; Conboy & Mills, 2006) or comprehension and production level (e.g., Friedrich & Friedrici, 2004, 2010; Torkildsen et al.,

2006) affects the pattern of brain activity during word processing, and thus we expected that children in both age groups with high productive vocabulary scores would have different distribution and/or lateralization of the N400 effect than those with low productive vocabulary score

2. Material and methods

2.1. Subjects

Twenty (6 girls and 14 boys) 18-month-old (range: 17 months 21 days to 19 months 2 days, mean: 18 months and 13 days) and 23 (16 girls and 7 boys) 24-month-old (range: 23 months 19 days to 25 months 24 days, mean: 24 months and 17 days) children from monolingual French-speaking families participated in the experiment. The infants were recruited from a database of parents who volunteered to participate in child development studies, and came from diverse socio-economic backgrounds in the Parisian region. All infants were born full-term and none of them suffered from hearing or language impairment. The parents gave informed consent before participation. Seventeen and 16 additional children of 18- and 24-month-olds, respectively, were recruited but their data were rejected due to noisy data (n = 28), refusal to put the cap (n = 4), or unfinished experiment (n = 1). The comprehensive and productive vocabulary size was tested by a French translation and adaptation of the McArthur Communicative Development Inventory for Words and Sentences (Fenson et al., 1993). Parents filled the inventory at home either before coming to the laboratory or within a week or two after the experiment. Altogether, the inventory contains 748 words. Parents of 36 children (out of 43) returned the inventory.

2.2. Stimuli

The stimuli were one-, two-, or three-syllable French basic level nouns from seven different categories (animals, clothes, body parts, food, furniture, transportation, and household items). The word categories were chosen from the McArthur Communicative Development Inventory for Words and Sentences. The stimuli were arranged into 72 prime-target word pairs (Appendix A).

There were 36 words for each trial type (unrelated primes, related primes, and target words). Half of the word pairs consisted of categorically (but not associatively) related words (e.g., train-bike) and half of them of categorically unrelated words (e.g., chicken-bike). Each target word was presented twice; once in the related and once in the unrelated condition. The duration of related and unrelated prime words varied between 435 ms and 1066 ms (mean duration = 714 ms, SD = 165 ms) and 375 ms and 975 ms (mean duration = 705 ms, SD = 169 ms), respectively. The duration of target words varied between 284 ms and 992 ms (mean duration = 680 ms, SD = 187 ms). The mean number of syllables was 1.75, 1.56, and 1.67 for unrelated prime, related prime, and target words, respectively. The number of phonemes was 4.11, 3.97, and 3.64 for unrelated, related, and target words, respectively. None of the variables (durations, syllables, or phonemes) differed significantly for unrelated prime, related prime, or target words (all p-values > 0.05). The number of stimulus words known by 18-month-olds was smaller (18.7, 17.2, and 18.8 unrelated, related, and target words, respectively) than that by 24-month-olds (30.2, 28.6, and 29.4 for unrelated, related, and target trials, respectively) ($F(1,110)=175.5$, $p < 0.001$), but there was no significant effect of trial types on the number of comprehended words in either age group (all $p > 0.05$). The words were recorded and edited with Cool Edit 2000 (Syntrillium Software Corp., Phoenix, AZ) and Praat (version 5.3.02) programs. The speakers were four native French female speakers and they were asked to pronounce the words slowly. We used words pronounced by four different speakers to have variability in sound level features and not to allow children to rely on acoustic features. Furthermore, talker variability has been shown to facilitate word learning in children (Richtsmeier, Gerken, Goffman, & Hogan, 2009) and retrieval from long-term memory in adults (Goldinger, Pisoni, & Logan, 1991). The sound levels were normalized among the speakers and words.

2.3. Experimental procedure

Infants were seated on their caregiver's lap or by themselves in a dimly lit room facing loudspeakers and a computer screen at the distance of 100-120 cm. Parents were informed of the purpose of the study before signing the consent. They were instructed not to communicate verbally or non-verbally with their infant during the actual experiment. Children were allowed to play with small toys positioned on the table in front of them during the experiment. Pictures from children's books were also presented on the computer screen during the experiment. New pictures appeared every 15 seconds. The changing of pictures was not synchronized with auditory stimulation.

The interstimulus interval (ISI) was 200 ms between the prime and the target words in each word pair and the intertrial interval (ITI) between the word pairs was 2200 ms. Stimulus onset asynchrony (SOA) varied between 635 ms to 1266 ms (mean SOA = 910 ms, SD = 166 ms). Each stimulus pair (72 pairs) was presented twice during the experiment. The experiment was divided into the four blocks and there was a little break between the blocks. One block consisted of 36 trials; 18 related and 18 unrelated word pairs. The same target word (e.g., bike) was presented for related (e.g., train-bike) and for unrelated (e.g., chicken-bike) conditions within the same block but the same pairs were never repeated within the block. Prime and target words in a given trial were always spoken by a different speaker. The whole experiment lasted 10 minutes.

2.4. EEG Recording and Analysis

Continuous electroencephalogram (EEG) was recorded (bandpass = 0.1–100 Hz, sampling rate = 250 Hz) from 62 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0) referenced to the vertex during the acquisition. Impedances were kept below 50 kΩ. EEG was filtered (0.3–30 Hz), segmented (1200 ms, beginning 200 ms before target word onset), and ocular artefacts were removed with an ocular artefact removal (OAR) algorithm (Gratton, Coles, & Donchin, 1983). The 200-ms pre-stimulus period determined the baseline for amplitude measures. The epochs including artefacts (eye-movements, blinks, motion artefacts exceeding ± 150 μV in any channel) were excluded. The epochs with more than 20 contaminated channels were also rejected. Individual bad channels were replaced using spherical spline interpolation. The epochs were averaged separately for each subject and type of target (related and unrelated) word. The averaged waveforms were re-referenced to the average reference and baseline corrected. The average reference has been suggested to provide an inactive reference, which is computed by subtracting the mean of all electrodes from each channel, and it suitable for high-density montages (e.g., Dien, 1998). The epochs were grand-averaged across all participants in each age group for the type of target word. Participants with less than 10 trials *per* target word type were rejected. The mean number of trials after the artefact rejection was 25 (12-42 trials) and 22 (10-51 trials) for related and 26 (10-41 trials) and 21 (10-50 trials) for unrelated target words in 18- and 24-month-olds, respectively.

2.5. Statistical analysis

The analysis of variance (ANOVA) included the following factors: trial type (related *versus* unrelated target word), area (frontal, central, and parietal-occipital), hemisphere (left *versus* right), and time interval (five 200-ms time windows starting from 0 ms to 1000 ms) as within-subject factors, and age group (18-month-olds *versus* 24-month-olds) and vocabulary group (high producers *versus* low-producers) as a between-subject factor. Nine electrode positions were included in each recording area (thus covering almost exclusively the sensor net), but the midline recording sites were excluded from the statistical analyses. The frontal, central and the parietal-occipital recording sites included the following electrode positions: 8, 9, 11, 12, 13, 14, 15, 16, and 19, (frontal left), 1, 2, 3, 6, 57, 58, 60, 61, and 62 (frontal right), 5, 17, 18, 20, 21, 22, 23, 24, and 25 (central left), 43, 47, 50, 52, 53, 54, 55, 56, and 59 (central right), 26, 27, 28, 29, 31, 32, 33, 36, and 37 (left parietal), and 40, 41, 42, 44, 45, 46, 48, 49, and 51 (right parietal). According to the 10-10 international electrode position system, the electrode placements 13 and 62 in frontal area are approximately located around F3 and F4 positions, placements 17 and 54 in central area around C3 and C4 positions, and placements 28 and 46 in parietal-occipital area around P3 and P4 positions (see Figs. 1 and 2). The statistical analyses were conducted using the SPSS statistical package (IBM SPSS Statistics, version 20) and all amplitude results of the ANOVAs were Greenhouse–Geisser corrected for nonsphericity when appropriate.

3. Results

3.1. ANOVAs by age group

The distributions of the ERPs for the unrelated and related target words for the two age groups are illustrated in Figures 1 and 2. There was no main effect of *age group* ($F(1,41)=0.956$, $p=0.334$) on the magnitude of negativity but interactions of *age group* with *trial type* and *area* ($F(2,82)=2.66$, $p=0.096$) and *trial type* and *area* and *time interval* ($F(8,328)=2.29$, $p=0.069$) were close to significant. In the following analysis, we examined the two age groups separately.

In 24-month-olds, the N400-like effect was obtained at the right parietal-occipital recording sites. At the frontal recording sites, the effect was reversed, that is, the negativity was more pronounced for related than for unrelated target words (Fig. 3). The statistical analyses confirmed these findings as shown by several significant interactions: *trial type x area x time interval* ($F(8,176)=4.29$, $p<.01$), *area x hemisphere x time interval* ($F(8,176)=2.94$, $p<.05$), *trial type x area x hemisphere x time interval* ($F(8,176)=2.95$, $p<.05$), and *area x time interval* ($F(8,176)=4.09$, $p<.01$). In follow-up 2-way ANOVAs, it was shown that there was a significant interaction between *trial type x time interval* at the frontal ($F(4,88)=4.41$, $p<.05$) and parietal-occipital ($F(4,88)=4.64$, $p<.01$), but not at central, recording areas. At the frontal recording area, the slow negativity was more pronounced for related than for unrelated targets during the first and the second time interval over the both hemispheres ($t(22)= -2.24$, all $p<.05$). At the parietal-occipital recording sites, the N400 effect was more pronounced for unrelated than for related targets during the first (mean amplitude of the effect -2.04 µV), second (-3.28 µV), and the third (-2.70 µV) time intervals over the right hemisphere ($t(22)= 2.34$, $p <.05$). In addition, we also tested whether the ERPs were different for prime and target words. In this analysis, we included only the recordings at the right posterior parietal recording area (during the time interval of 0-1000 ms) in which the significant effect between unrelated and related target words was found. The results showed that there was a significant main effect of *trial type* on the magnitude of slow wave ($F(2,44)=3.55$, $p<.05$). The slow wave was more negative for unrelated target (mean -1.41 µV) than for prime (mean 0.69 µV) words ($t(22)=2.03$, $p=0.054$), but there was no difference between prime and related target (mean 0.62 µV) words ($t(22)=0.89$, $p=0.93$).

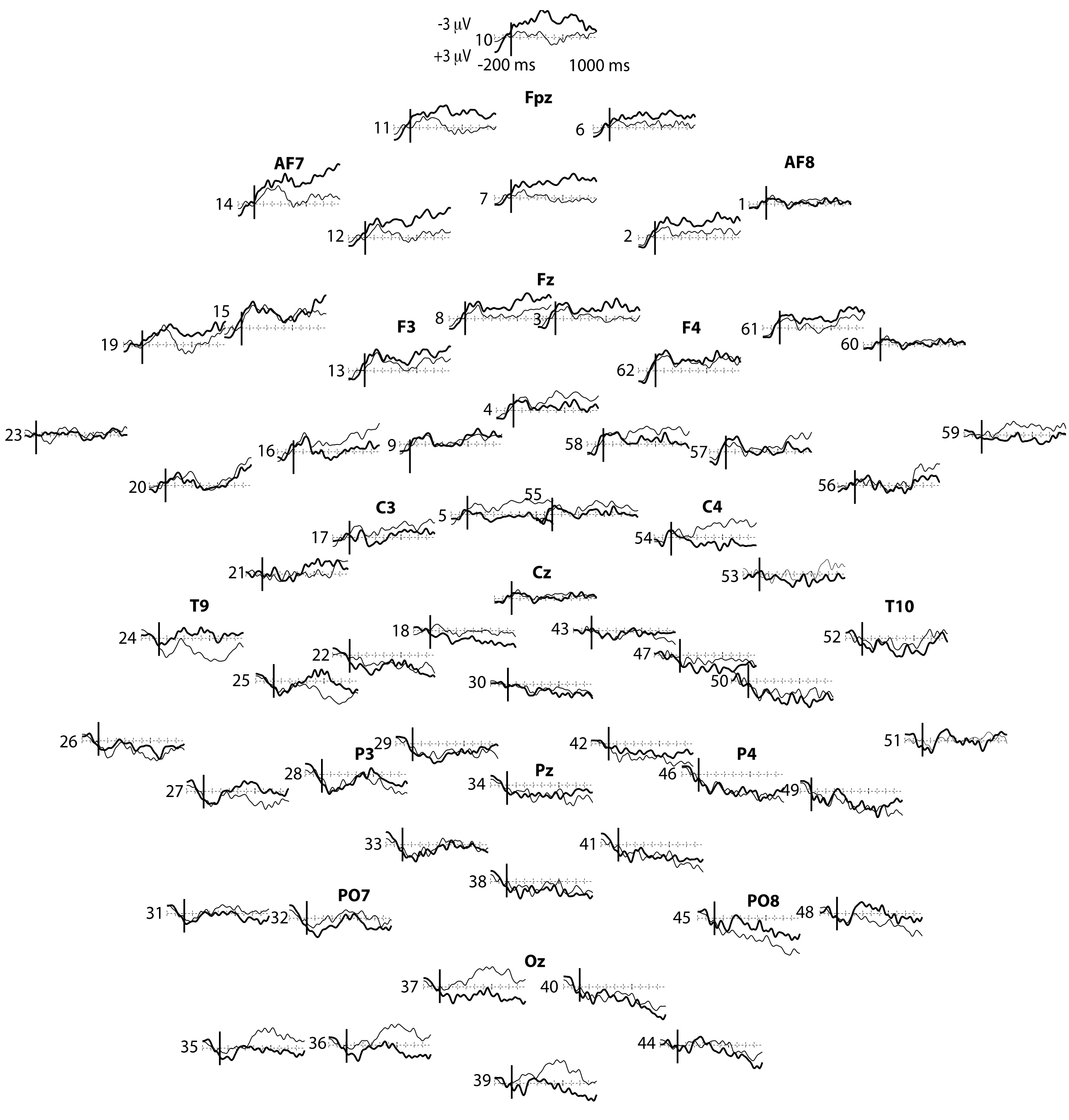


Fig. 1. ***Grand-averaged waveforms for related (thin line) and unrelated (thick line) target words in 18-month-old children.*** The sensor positions in GSN and some approximate electrode placements according to the 10-10 international electrode position system are indicated. The frontal, central and the parietal-occipital recording areas (used in the statistical analyses) included the following electrode positions: 8, 9, 11, 12, 13, 14, 15, 16, and 19, (frontal left), 1, 2, 3, 6, 57, 58, 60, 61, and 62 (frontal right), 5, 17, 18, 20, 21, 22, 23, 24, and 25 (central left), 43, 47, 50, 52, 53, 54, 55, 56, and 59 (central right), 26, 27, 28, 29, 31, 32, 33, 36, and 37 (left parietal), and 40, 41, 42, 44, 45, 46, 48, 49, and 51 (right parietal). The vertical line illustrates the target word onset.

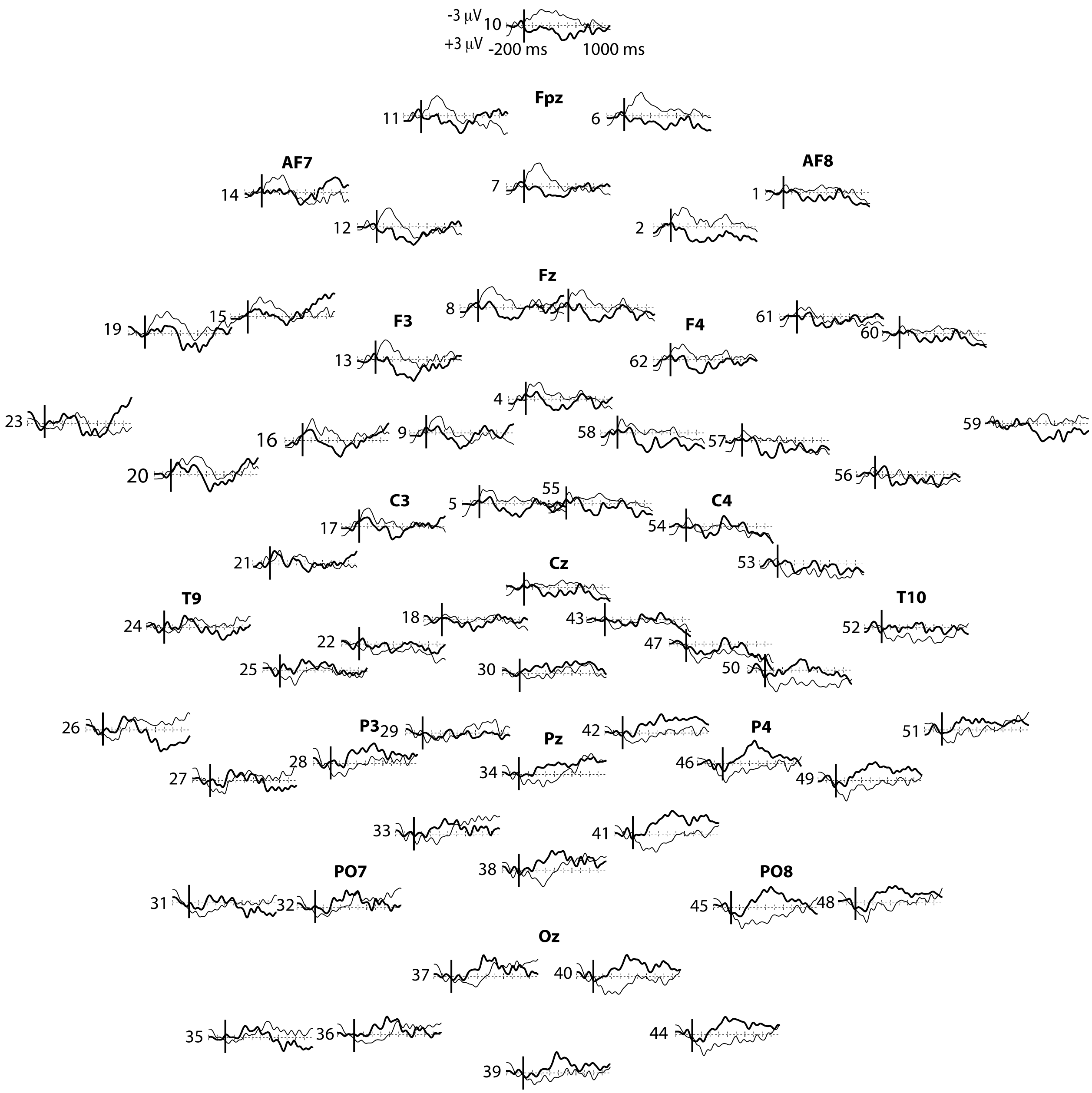


Fig. 2. ***Grand-averaged waveforms for related (thin line) and unrelated (thick line) target words in 24-month-old children***. Other explanations as in Fig. 1.

In 18-month-olds, the statistical analyses showed that the interactions between *trial type x area x hemisphere* ($F(2,38)=3.31$, $p=0.058$) and *area x hemisphere x time interval* ($F(8,152)=2.54$, $p=0.072$) did not reach significance. In further 2-way ANOVAs, it was shown that there were no significant interactions between *trial type x time intervals* at any recording areas (Fig. 4), showing that slow negativity was not significantly different between different target word conditions. Similar to 24-month-olds, we also tested whether the ERPs were different for prime and target words. The results showed that there was a close to significant main effect of *trial type* on the magnitude of slow wave ($F(2,38)=3.15$, $p=0.060$). Both related (mean 2.04 µV, $t(19)=-2.15$, $p<0.05$) and unrelated words (mean 1.51 µV, $t(19)=-2.15$, $p<0.05$) produced more positive response than prime words (-0.11 µV).

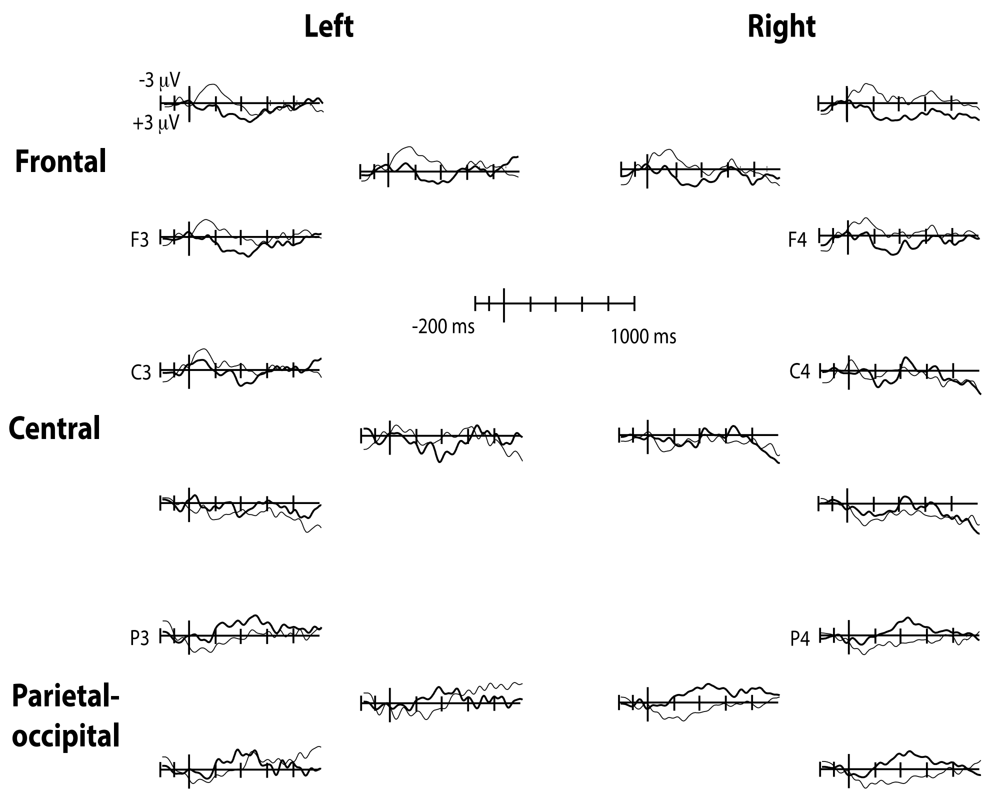


Fig. 3. ***Grand-averaged waveforms for related (thin line) and unrelated (thick line) target words in 24-month-old children.*** Three examples of recordings in each area (frontal, central, and parietal-occipital) and in both hemispheres are illustrated. Some approximate electrode placements according to the 10-10 international electrode position system are indicated (F3, F4, C3, C4, P3, and P4). The vertical line illustrates the target word onset. The significant N400 effect was found over the right parietal-occipital recording area.

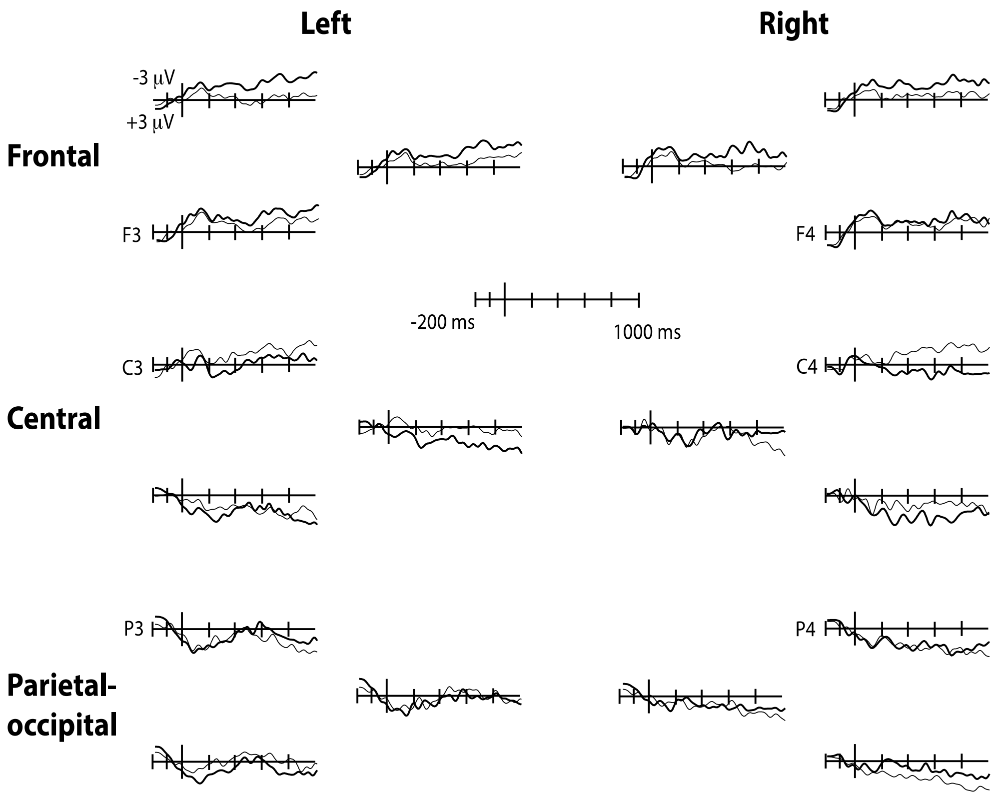


Fig. 4. ***Grand-averaged waveforms for related (thin line) and unrelated (thick line) target words in 18-month-old children.*** Three examples of recordings in each area (frontal, central, and parietal-occipital) and both hemispheres are illustrated. Some approximate electrode placements according to the 10-10 international electrode position system are indicated (F3, F4, C3, C4, P3, and P4). The vertical line illustrates the target word onset.

3.2. ANOVAs by productive groups in 18-month-olds

The participants were divided into two vocabulary groups based on their productive vocabulary scores obtained in McArthur Communicative Development Inventory for Words and Sentences. The vocabulary scores were not obtained from two children, and thus, these participants were excluded from this analysis. The mean vocabulary score was calculated for each participant and the median score of all participants was used to divide them into two groups, named low and high producer groups. The mean number of words produced by 18-month-olds was 44 (SD = 53). In the low producer group, the average score was 10 words (range 0-24 words) and in the high producer group the average score was 78 words (range 25-214 words). The difference between scores was statistically significant between the groups ($t(16)=-3.49$, $p<0.005$).

The effect of *vocabulary group* was not, however, significant when looking at the magnitude of the N400 effect ($F(1,16)=0.001$, $p=0.973$). In the following analysis, we examined the two vocabulary groups separately. We reasoned that even though the N400 effect was not significant when all 18-month-olds were included in the statistical analysis, there was a tendency for significance (e.g., *trial type x area x hemisphere interaction p=0.058*), and thus, it was possible that vocabulary scores were played a role in our results. Indeed, a significant interaction between *trial type x area x hemisphere* ($F(2,16)=4.87$, $p<0.05$) was found in high producer group, but not in the low producer group ($F(2,16)=0.006$, $p=0.985$). In our earlier analysis of 24-month-olds, the effect was found during the first, second, and the third time interval over the right parietal-occipital area, and so we conducted another statistical analysis on both 18-month-old groups that included only this recording area and these time windows. The results showed that the main effect of *trial type* was close to significance level ($F(1,8)=4.42$, $p=0.069$) in the high production group, but no difference was observed in the low production group ($F(1,8)=0.673$, $p=0.436$). A close to significant difference was found in the second (200-400 ms) ($t(8)=2.0$, $p=0.081$) and the third (400-600 ms) interval ($t(8)=1.92$, $p=0.092$) in high producers. The difference between the groups was statistically close to significance ($t(16)= 2.000$, $p=0.063$) (Fig. 5a). Frontally distributed negative response to related target words was not significantly different from similar responses to unrelated words either in the high ($F(1,8) = 4.23$, $p=0.074$) or the low ($F(1,8) = 0.26$, $p<0.624$) producer groups.

3.3. ANOVAs by productive groups in 24-month-olds

We also tested the effect of vocabulary size on the magnitude of N400 effect in 24-months-olds. The vocabulary scores were not obtained from all children, and thus these participants ($n=4$) were excluded from the analysis. The mean number of words produced by 24-month-olds was 229 (SD = 149). In the low producer group, the average score was 107 words (range 4-238 words), while the average score in the high producer group was 339 words (range 243-555 words). The difference between scores was statistically significant between the groups ($t(17)=-5.40$, $p<0.001$).

The effect of *vocabulary group* was not, however, significant on the magnitude of the N400 effect ($F(1,17)=0.202$, $p=0.658$). In the following analysis, we examined the two vocabulary groups separately. There was a close to significant interaction (*trial type x area x hemisphere*) in high producer group ($F(2,18)=3.24$, $p=0.066$), but not in the low producer group ($F(2,16)=0.115$, $p=0.892$). Next, we tested whether the N400 effect obtained over the right parietal-occipital recording sites during the first, second, and the third time interval was significant in both vocabulary groups. A visual inspection indicated that there was an N400 effect in both vocabulary groups in 24-month-olds, but a significant main effect of *trial type* on the magnitude of the N400-like effect was obtained only in the high producer group ($F(1,8)=9.50$, $p<0.05$), and not in the low producer group ($F(1,8)=0.96$, $p=0.356$; Fig. 5a). In the high producers, a significant difference was found in the second time interval (200-400 ms) ($t(9)=2.43$, $p<0.05$), and close to significant differences were found in the first (0-200 ms) ($t(9)=1.92$, $p=0.087$) and the third (400-600 ms) time intervals ($t(9)=2.24$, $p=0.052$). However, the effect size was not statistically significant between the groups ($t(17)=0.624$, $p=0.541$), indicating that even the magnitude of the N400-like response varies according to the productive ability in 24-month-olds, the difference was not significant (Fig. 5a).

Similar to the N400-like effect, more negative response to related than to unrelated target words over the frontal left and right recording sites during the first and the second time interval was significant in the "higher" producer group ($F(1,9) = 7.22$, $p<0.05$) but not in the "lower" producer group ($F(1,9) = 3.34$, $p<0.105$) in 24-month-olds. In "lower" producer group, there was a significant main effect of hemisphere ($F(1,8) = 5.39$, $p<0.05$). The effect was stronger over the left than the right hemisphere, but not statistically significantly ($t(8)=1.37$, $p=0.207$).

We also analysed the *trial type* effect in an ANOVA with both *age* and *vocabulary group* as between-subjects factors. In this analysis, we included the first, second, and the third time interval over the right parietal-occipital area in which the significant *trial type* effect was earlier found. As indicated earlier, there was a significant main effect of *trial type* on the magnitude of negativity ($F(1,33)=4.95$, $p<0.05$). A close to significant main effect was found only for *age group* ($F(1,33)=3.74$, $p=0.062$). Also, the interaction of *trial type* with the *vocabulary group* ($F(1,33)=3.49$, $p=0.071$) was close to significant. A significant main effect of *trial type* (including both 18- and 24-month-olds) was found in high producers ($F(1,18)=13.53$, $p<0.005$), but not in low producers ($F(1,17)=0.045$, $p=0.835$; Fig. 5b).

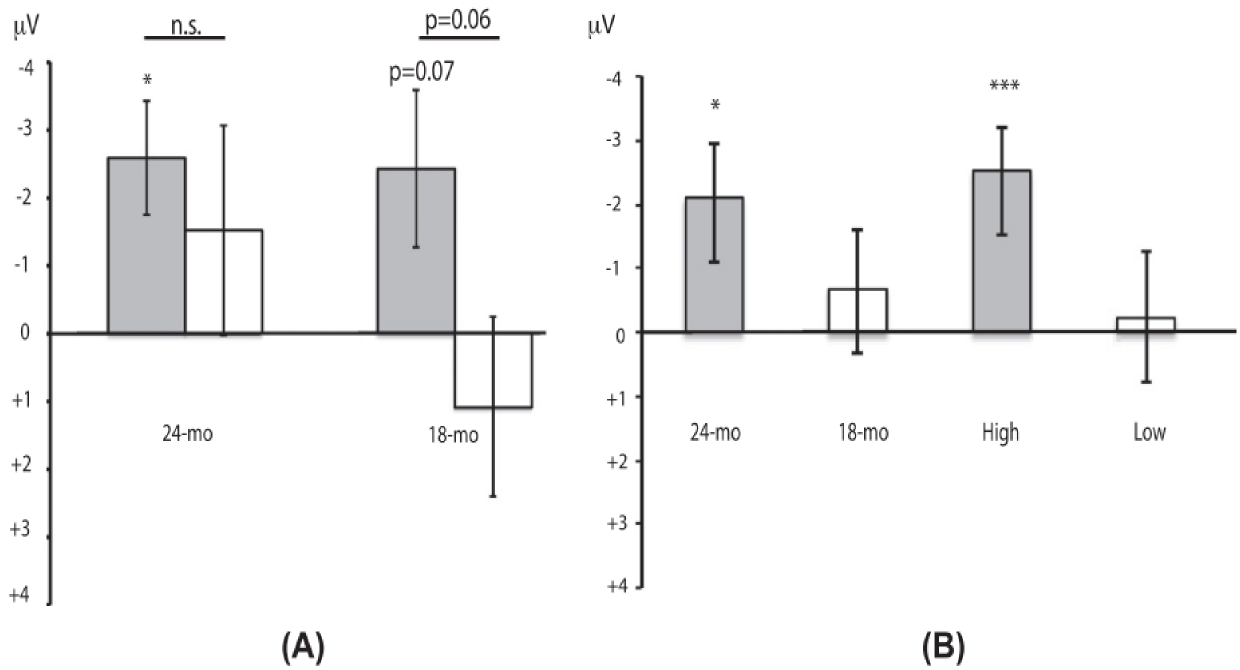


Fig. 5. A. ***The magnitude of N400 effect in high and low 24- and 18-month-old word producers in the right parietal-occipital recording area.*** Grey columns illustrate the high producer group and the white columns the low producer group. **B.** ***The magnitude of N400 effect in 24- and 18-month-olds (both in high and low word producers) and in high and low producers (both in 18- and 24-month-olds) in the right parietal-occipital recording area.*** The vertical bars illustrate the standard error of means. * $p < 0.05$, ** $p < 0.005$, n.s. statistically non-significant

4. Discussion

The aim of our study was to investigate whether the lexical-semantic language system is organized by taxonomic relations between word pairs in 18- and 24-month-old monolingual French learning children. The participants were exposed to a semantic priming task in which they heard semantically related (e.g., train-bike) and unrelated (e.g., chicken-bike) spoken word-pairs. An N400-like effect to the target words was obtained in 24-months olds, but it was absent in 18-months olds. However, in a group of 18-month-olds with higher production ability, the N400-like effect was observed similarly to 24-month-olds. Our results suggest that words are organized by semantic taxonomic categories in the mental lexicon of children at the age of two years and even earlier in children with a high vocabulary size.

The N400 effect in 24-month-olds was obtained focally over the right posterior-occipital recording sites and no significant effect was found over the other recording sites. In adult participants, the visual N400 effect is typically found over the right posterior recording sites, but in auditory tasks, asymmetrical effects are less consistent (for review, see van Petten & Luka, 2006). In children, an N400-like incongruity effect in a picture-word task was shown to be stronger and temporally more extended over the left hemisphere recording sites, but still, significant hemispheric differences were not found (Friedrich & Friedrici, 2004). Moreover, an N400-like priming effect for the spoken words was reported to be larger over the left than the right recording sites (Torkildsen et al., 2007). In that study, the effect was obtained over the fronto-central scalp positions whereas in our study, the effect was seen over the parietal-occipital positions. The front-central distribution in their study might be, however, associated with the recruitment of attention in the task since the words were presented together with visual cartoon characters to catch children's attention. The negative waveforms for related and unrelated target words started to deviate from each other already during the first time window (0–200 ms) in our study, and the effect lasted until 600 ms, in contrast to the earlier studies in which the effect was obtained later (e.g., Friedrich & Friedrici, 2004; Torkildsen et al., 2007). However, in another study, where the N400 effect was compared in visual and auditory modalities (Holcomb & Neville, 1990), the effect in the auditory modality was obtained already in a 150–300 ms time interval in contrast to visual modality, where the effect was obtained in a 300–500 ms time interval, indicating that priming processes are not identical in two modalities. In addition to modality-specific differences in priming, there is also a possibility that the early part of the negativity is not part of the N400 effect, but it reflects the P100 component, shown to be modulated by word familiarity (Mills et al., 1997), word repetition (Friedrich and Friedrici, 2011), and also by priming when tested in a memory test after training of novel word-picture pairings (Friedrich & Friederici, 2011).

In the present study, the N400 priming effect was obtained in 24-month-olds, but not yet in 18-month-olds. These results are in accordance with earlier behavioural findings (Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009), showing that behavioural priming effect occurs in 21- and 24-month-olds, but not yet in 18-month-olds. Here, the semantically related word pairs were taxonomically related, whereas in previous mentioned behavioural studies, the related word pairs were both taxonomically and associatively related. In behavioural studies, associative relatedness between prime-target word pairs has been shown to boost the strength of priming effect. However, ERP technique is more sensitive to detect subtle differences in processing of unrelated and related word pairs, and it remains to be seen whether the N400 effect in 18-month-olds would have been obtained in our study if associative prime-target word pairs were used. Compared with prime words, both related and unrelated target words produced more *positive* response in 18-months-olds, whereas in 24-month-olds, the response to unrelated target words was more *negative*. Lack of negative response to target words (in comparison with the prime words) may indicate that the prime words activated less specified semantic network in 18-month-old children. It should be noted that even the target words were the same in the related and unrelated conditions, the prime words were not (e.g., train-bike and chicken-bike). However, there was no difference in the number of comprehended words in different conditions in either age group, and thus, it is unlikely that using different prime words would have affected our results.

Another possibility for the absence of the N400 effect in our 18-month-olds could be related to linguistic processing speed. It has previously been shown that 24-months-olds initiate their gaze in an IPL task well before a word has finished being spoken, whereas 15- and 18-month-olds are significantly slower, suggesting that speed and efficiency of speech processing increases during the second year of life (Fernald, Pinto, Swingley, Weinberg, McRoberts, 1998). In our study, the average SOA (stimulus onset synchorony) between the prime and the target word was around 900 ms. It is, thus, possible that the SOA was not long enough for 18-month-olds to activate their semantic representations after prime word presentation. In adults, the N400 effect during an auditory dichotic listening task was obtained only when the SOA between the prime and target words was 800 ms, but not when it was shorter in contrast to visual modality in which the effect was obtained in shorter SOA conditions (Anderson and Holcomb, 1995). Whether a longer SOA would have allowed the 18-month-olds to activate semantic representations and elicit N400 priming effect remains to be further studied. Another possibility is that the memory representations for words are not yet well established in 18-months-olds, especially in those with low word production ability. It has been suggested before that even though the brain structures realizing the N400 mechanisms might be mature in early infancy, the N400 effect may not always be elicited due to weakly established lexical-semantic memory representations (Friedrich & Friedrici, 2010).

The age from 20 to 22 months is typically associated with a burst in vocabulary size for both comprehension and production (Reznick & Goldfield, 1992; see also, Ganger & Brent, 2004). This burst in vocabulary size has been suggested to be associated with development of naming insight, ability to categorize objects, or advancing in word segmentation (for review, see Ganger & Brent, 2004). Our results showed, at least for 18-month-olds who had higher production ability, that an N400 effect over the right parietal-occipital recording area can be observed, which is similar to 24-month-olds. This suggests that vocabulary size influences the N400 priming effect, which fits with previous research that suggests vocabulary effects can occur in the right hemisphere (Friedrich & Friedrici, 2004; 2010; Torkildsen et al., 2006; cf. Torkildsen et al., 2008). When both the *age* and the productive *vocabulary groups* were included in the same analysis as between-subject factors, it was shown that the *vocabulary* but not the *age group* interacted with the trial type, suggesting that the former may influence the magnitude of N400 effect more than the latter. In our study, we analysed production vocabulary, and not comprehension vocabulary, as production is likely be more reliable measure of vocabulary size in young children. Results showed that low and high producers did not have a different distribution and/or lateralization, but the effects were stronger in the high producers in both age groups in the right hemisphere.

In addition to the N400 semantic priming effect, a stronger negativity for *related* than for *unrelated* target words was observed over the frontal recording sites in 24-month-olds, but not in 18-month-olds. This relatedness effect was equally strong over the left and the right recording sites. Similar relatedness effect has been found earlier over the frontal and temporal recording sites (e.g., Friedrich & Friedrici, 2005b; Torkildsen et al., 2007) and it has been suggested that this effect is associated with processing of acoustic-phonological information of expected target word. Also in adult studies using event-related functional magnetic resonance imaging (fMRI), the stronger effect for related than for unrelated target words has been associated with visual imagery and phonological processes, but not with semantic priming (Kotz, Cappa, von Cramon, & Friedrici, 2002; Rossell, Price, & Nobre, 2003). It remains unclear why the effect was not found in 18-months-olds in the current study. In the current study we used a common average reference, whereas in earlier N400 studies in infants a linked-mastoid reference was used (e.g., Friedrich & Friedrici, 2004, 2005b,c; Torkildsen et al., 2007). When conducting high-density recordings, an average-reference procedure is considered appropriate because of its insensitivity to the influence of scalp currents near any single electrode (Dien, 1998; Picton et al., 2000). Furthermore, a comparison of distribution of N400 effect with other studies using a linked mastoid reference (e.g., Friedrich and Friedrici, 2004, 2005c) shows a relatively similar distribution of the N400 effect across studies.

5. Conclusions

Our results suggest that words are organized by semantic categories in the mental lexicon of children at the age of two years and even earlier in children with a high vocabulary size. This was indicated by the appearance of N400 effect in a semantic priming task in 24-month-olds, and in 18-month-olds with a high vocabulary size. It has been suggested that concepts in semantic memory are organized by semantic holistic units (e.g., nodes) which are connected to each other by learned associations or by distributed interconnected features (for review, see Hutchison, 2003). Holistic models assume that activation spreads from one activated semantic representation to another semantically associated representation (e.g., Collins & Lotus, 1975; Neely, 1977; Hutchison, 2003) whereas distributed models propose that processing of a concept facilitates the processing of a related concept because their "feature overlap". The occurrence of N400 effect in developing brain is suggested to be related to brain maturation, established and specified lexical-semantic memory representations, and activation of semantic representations with similar features (Friedrich & Friedrici, 2010). We believe that by the age of two years children are capable of automatically activate semantic representations having similar features with the prime word. This seems to happen even earlier if language capacity (as measured by word production) is high, probably indicating that word representations are already well established and specified. Whether the occurrence of the N400 effect is associated, in addition to age and vocabulary size, with speed of language processing, type of relation between word pairs, and other developing cognitive abilities, such as attention, or working memory capacity, needs to be further investigated.

Acknowledgements

We wish to thank all the parents participating to the study with their children.

6. References

Anderson, J.E., & Holcomb, P.J. (1995). Auditory and visual semantic priming using different stimulus onset asynchronies: An event-related brain potential study. *Psychophysiology*, 32, 177-190.

Arias-Trejo, N., & Plunkett, K. (2009). Lexical-semantic priming effect during infancy. *Phil. Trans. R. Soc. B, 364*, 3633–3647.

Becker, C. A. (1976). Allocation of attention during visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *2*, 556–566.

Bentin, S., McCarthy, G., & Wood, C. C. (1985). Event-related potentials, lexical decision and semantic priming. *Electroencephalography and Clinical Neurophysiology, 60*, 343–355.

Bergelson, E., & Swingley, D. (2012). At 6-9 months, hulan infants know the meanings of many comon nouns. *Proceedings of the National Academy of sciences, 109 (9),* 3253-3258.

Besson, M., Boaz, T., Fischler, I., & Raney, G. (1992). Effects of automatic associative activation on explicit and implicit memory tests. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 89–105.

Brown, C. M., Hagoort, P., & Chwilla, D. J. (2000). An event-related brain potential analysis of visual word priming effects. *Brain and Language*, *72*, 158–190.

Chwilla, D. J., Brown, C. M., & Hagoort, P. (1995). The N400 as a function of the level of processing. *Psychophysiology, 32*, 274–285.

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, *82*, 407–428.

Conboy, B.T., & Mills, D.L. (2006). Two languages, one developing brain: event-related potentials to words in bilingual toddlers. *Developmental Science, 9*, 1–12.

Deacon, D., Breton, F., Ritter, W., & Vaughan, H. G., Jr. (1991). The relationship between N2 and N400: Scalp distribution, stimulus probability, and task relevance. *Psychophysiology, 28*, 185–200.

Dien, J. (1998). Issues in the application of the average reference: Review, critiques, and recommendations. *Behavior Research Methods, Instruments & Computers,* 30, 34-43.

Dombrowski, J.-H. & Heil, M. (2006). Semantic activation, letter search and N400: A reply to Mari-Beffa, Valdes, Cullen, Catena and Houghton 2005. *Brain Research, 1073–1074*, 440–443.

Federmeier, K. D., & Kutas, M. (1999). A rose by any other name: Long-term memory structure and sentence processing. *Journal of Memory and Language, 41*, 469-495.

Fenson, L., Dale, P., Reznick, S., Thal, D., Bates, E., Hartung, J., Pethick, S. & Reilly, J. (1993). *MacArthur Communicative Development Inventories: User's guide and technical manual.* San Diego, CA: Singular Publishing Group.

Fernald, A., Zangl, R., Portillo, A.L., & Rachman, U.A. (2008). Looking while listening: using eye movements to monitor spoken language comprehension by infants and young children. *In: Sekerina, I.A., Fernández, E.M., & Clahsen, H. (2008), Developmental Psycholonguistics: On-line methods in children's language processing, John Benjamins: Amsterdam* (pp. 97-135).

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 (3),* 228-231.

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*, 1465–1477.

Friedrich, M., & Friederici, A. D. (2005a). Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. *NeuroReport, 16*(6), 653-656.

Friedrich, M., Friederici, A. D. (2005b). Phonotactic knowledge and lexical-semantic processing in one-year-olds: brain responses to words and nonsense words in picture contexts. *Journal of Cognitive Neuroscience, 17*, 1785-1802.

Friedrich, M., & Friederici, A. D. (2005c). Semantic sentence processing reflected in the event-related potentials of one- and two-year-old children. *NeuroReport, 16*(16), 1801-1804.

Friedrich, M., & Friederici, A.D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43*, 1–12.

Friedrich, M., & Friederici, A.D. (2010). Maturing brain mechanisms and developing behavioral language skills. *Brain and Language*, 114, 66-71.

Friedrich, M., & Friedrici, A.D. (2011). Word learning in 6-month-olds: fast encoding-weak retention. *Journal of Cognitive Neuroscience*, 23, 3228-3240.

Ganger, J., & Brent, M.R. (2004). Reexamining the vocabulary spurt. *Developmental psychology, 40 (4)*, 621-632.

Goldinger, S.D., Pisoni, D. B., & Logan, J.S. (1991). On the nature of talker variability effects on recall of spoken word lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 152-162.

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

Gratton, G., Coles, M.G.H., & Donchin, E. (1983). A new method for off-line removal of ocular artifacts. *Electroencephalography and Clinical Neurophysiology, 55*, 468–484.

Heil, M., Rolke, M., & Pecchinenda, A. (2004) Automatic semantic activation is no myth. Semantic context effects on the N400 in the letter-search task in the absence of response time effects. *Psychological Science, 15,* 852–857.

Holcomb, P.J. (1988). Automatic and attentional processing: an event-related brain potential analysis of semantic priming. *Brain and Language, 35 (1),* 66-85.

Holcomb, P. J., & Neville, H. J. (1990). Auditory and visual semantic priming in lexical decision: A comparison using event-related brain potentials. *Language and Cognitive Processes, 5*, 281–312.

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

Kotz, S. A., Cappa, S. F., von Cramon, D. Y., & Friederici, A. D. (2002). Modulation of the lexical-semantic network by auditory semantic priming: An event-related functional MRI study. *Neuroimage, 17*, 1761–1772.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*, 203–205.

Kutas, M., & Hillyard, S. A. (1989). An electrophysiological probe of incidental semantic association. *Journal of Cognitive Neuroscience, 1,* 38–49.

Kutas, M., Van Petten, C., & Besson, M. (1988). Event-related potential asymmetries during the reading of sentences. *Electroencephalography and clinical Neurophysiology, 69,* 218-233.

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

Mari-Beffa, P., Valdes, B., Cullen, D. J. D., Catena, A., & Houghton, G. (2005). ERP analyses of task effects on semantic processing from words. *Cognitive Brain Research, 23,* 293–305.

Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90,* 227–234.

Mills, D.L., Coffey-Corina, S.A., & Neville, H.J. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *Journal of Cognitive Neuroscience, 5 (3),* 317-334.

Mills; D.L., Coffey-Corina, S., & Neville, H. (1997). Language comprehension and cerebral specialization from 13 to 20 months. *Developmental Neuropsychology, 13 (3),* 397-445.

Mills, D.L., Plunkett, K., Pratt, C., & Schafer, G. (2005). Watching the infant brain learn word: effects of vocabulary size and experience. *Child Development, 20,* 19-31.

Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General, 106*, 226–254.

Neely, J. H., & Keefe, D. E. (1989). Semantic context effects on visual word processing: A hybrid prospective-retrospective processing theory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (pp. 207–248). New York: Academic.

Neely, J. H., Keefe, D. E., & Ross, K. L. (1989). Semantic priming in the lexical decision task: Roles of prospective prime-generated expectancies and retrospective semantic matching. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 1003–1019.

Perrin, F., & García-Larrea, L. (2003). Modulation of the N400 potential during auditory phonological/semantic interaction. *Cognitive Brain Research, 17,* 36–46.

Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson, R. Jr., Miller, G.A., Ritter, W., Ruchkin, D.S., Rugg, M.D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology***,** 37, 127-152.

Rämä, P., Relander-Syrjänen, K., Carlson, S., Salonen, O., & Kujala, T. (2012) Attention and semantic priming in speech processing: an fMRI study. *Brain & Language, 122*, 114–119.

Relander, K., Rämä, P., & Kujala, T. (2009). Word semantics is processed whether or not speech is attended. *Journal of Cognitive Neuroscience, 21*, 1511-1522.

Reznick, J. S., & Goldfield, B. A. (1992). Rapid change in lexical development in comprehension and production. *Developmental Psychology, 28*, 406-413.

Richtsmeier, P.T., Gerken, L., Goffman, L., & Hogan, T. (2009). Statistical frequency in perception affects children's lexical production. *Cognition*, *111*, 372-377.

Rossell, S. L., Price, C. J., & Nobre, A. C. (2003). The anatomy and time course of semantic priming investigated by fMRI and ERPs. *Neuropsychologia, 41*, 550–564.

Silva Pereyra, J.F., Klarman, L., Lin, L. J-F., & Kuhl, P.K. (2005). Sentence processing in 30-month-old children: an event-related potential study. *Neuroreport, 16 (6)*, 645-648.

Styles, S. J., & Plunkett, K. (2009). How do infants build a semantic system? *Language and cognition*, *1-1*, 1–24.

Thierry, G., Vihman, M., Roberts, M. (2003). Familiar words capture the attention of 11-month-olds in less than 250 ms. *Neuroreport*, *14*, 2307-2310.

Torkildsen, J. vK., Sannerud, T., Syversen, G., Thormodsen, R., Simonsen, H.G., Moen, I., Smith, L., et Lindgren, M. (2006). Semantic organization of basic-level words in 20-month-olds: An ERP study. *Journal of Neurolinguistics, 19*, 431-454.

Torkildsen, J.K., Syversen, G., Simonsen, H.G., Moen, I., & Lindgren, M. (2007). Electrophysiological correlates of auditory semantic priming in 24-month-olds. *Brain & Language, 20 (4)*, 332-351.

Torkildsen, J.K., Svangstu, J.M., Hansen, H.F., Smith, L., Simonsen, H.G., Moen, I., & Lindgren, M. (2008). Productive vocabulary size predicts event-related potential correlates of fast mapping in 20-month-olds. Journal of Cognitive Neuroscience, 20(7), 1266-1282.

Van Petten, C., & Luka, B. J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and Language, 97*, 279–293.

Appendix A.

Related Prime	Unrelated Prime	Target Word
Eléphant (Elephant)	Avion (Plane)	Ours (Bear)
Train (Train)	Poule (Chicken)	Vélo (Bike)
Banane (Banana)	Dent (Tooth)	Biscuit (Cookie)
Pantalon (Pants)	Poubelle (Trash)	Bottes (Boots)
Lampe (Lamp)	Orange (Orange)	Boite (Box)
Cochon (Pig)	Fromage (Cheese)	Cheval (Horse)
Nez (Nose)	Beurre (Butter)	Bouche (Mouth)
Robe (Dress)	Lumière (Light)	Chemise (Shirt)
Chien (Dog)	Fille (Girl)	Lapin (Rabbit)
Cube (Block)	Canard (Duck)	Ballon (Balloon)
Carotte (Carrot)	Pied (Foot)	Fraise (Strawberry)
Table (Table)	Pull (Jumper)	Lit (Bed)
Enfant (Child)	Bateau (Boat)	Sœur (Sister)
Moto (Motor-Bike)	Lait (Milk)	Camion (Truck)
Ecureuil (Squirrel)	Voiture (Car)	Mouton (Sheep)
Langue (Tongue)	Cuillère (Spoon)	Oreille (Ear)
Main (Hand)	Pâtes (Pasta)	Visage (Face)
Verre (Glass)	Veste (Jacket)	Bouteille (Bottle)
Céréales (Cereal)	Genou (Knee)	Tartine (Toast)

Gâteau (Cake)	Cheveux (Hair)	Pain (Bread)
Tante (Aunt)	Poupée (Doll)	Dame (Lady)
Ventre (Tummy)	Viande (Meat)	Jambe (Leg)
Chaussure (Shoe)	Balai (Broom)	Manteau (Coat)
Armoire (Drawer)	Chapeau (Hat)	Chaise (Chair)
Confiture (Jam)	Tête (Head)	Pomme (Apple)
Jus de fruits (Juice)	Doigt (Finger)	Eau (Water)
Fourchette (Fork)	Couche (Diaper)	Bol (Bowl)
Balle (Ball)	Frère (Brother)	Jouet (Toy)
Bébé (Baby)	Bulles (Bubble)	Garçon (Boy)
Oncle (Uncle)	Oiseau (Bird)	Monsieur (Man)
Papillon (Butterfly)	Poussette (Stroller)	Chat (Cat)
Souris (Mouse)	Œuf (Egg)	Vache (Cow)
Lion (Lion)	Chocolat (Chocolate)	Poney (Pony)
Âne (Donkey)	Glace (Ice Cream)	Hibou (Owl)
Œil (Eye)	Montre (Watch)	Bras (Arm)
Oreiller (Pillow)	Joue (Cheek)	Canapé (Sofa)

[Study II: Published]

Cognitive and neural mechanisms underlying semantic priming during language acquisition

Louah Sirri [1], Pia Rämä [1, 2]

[1] Université Paris Descartes, Sorbonne Paris Cité, Paris, France

[2] CNRS, Laboratoire Psychologie de la Perception (UMR 8242), Paris, France

Corresponding author:

Louah Sirri

Laboratoire Psychologie de la Perception (CNRS, UMR 8242)

Université Paris Descartes

45, rue des Saints-Pères

75006 Paris

France

E-mail: louah.sirri@parisdescartes.fr

Fax : +33 (0) 1 42 86 33 22

Tel : +33 (0) 1 42 86 43 20

Highlights

- Semantic priming effects were obtained in 18-month-olds for spoken words
- Children were sensitive to semantic relations even before vocabulary spurt
- Amplitudes of the N2 and N400 were modulated by semantic relatedness
- Distribution of the late posterior negativity was modulated by relatedness and SOA
- Automatic and controlled mechanisms underlie priming during language acquisition

Abstract

Both automatic and controlled mechanisms have been shown to contribute to the magnitude of the N400 priming effect in adults. It has been proposed that at short SOAs, automatic processes are engaged, while at long SOAs, controlled processes are activated. Here, we explored whether the magnitude of language-related ERPs in 18-month-old children are SOA-dependent to further understand the developmental mechanisms underlying semantic priming during early language acquisition. Children were exposed to an auditory semantic priming task in two invariant SOA conditions (1000 ms and 1600 ms). The results showed that the amplitudes of N2, N400 and late posterior negativity (LPN) components were modulated by semantic relatedness, but only those of N2 and LPN were modulated by the SOA length. The amplitudes of the frontally distributed N2 were larger at long than at short SOAs, while the posteriorly distributed LPN was larger over the right hemisphere at the short SOA and more pronounced over the left hemisphere at the long SOA. These findings suggest that both automatic and controlled processes contribute to priming effects in the developing brain, but neural resources underlying these processes might differ.

Keywords: Semantic priming, language-related ERPs, automatic activation versus controlled mechanisms, language development

1. Introduction

1.1. Semantic priming and N400 effect in adults

For several decades semantic priming paradigms have commonly been used as a tool to better understand the organization of the mental lexicon and word retrieval from long-term memory (e.g., Kutas & Hillyard, 1989; Lucas, 2000; Meyer & Schvaneveldt, 1971). In lexical decision contexts, results generally show faster reaction times and more accurate responses to target words preceded by a semantically related word than to target words preceded by a semantically unrelated word (for a review, see Neely, 1991). Both automatic and controlled processes have been shown to influence the semantic priming effect (Neely & Keefe, 1989; Neely, Keefe, & Ross 1989). According to the automatic spreading activation model, a prime word activates related representations in a semantic network, reflecting links previously established between words. It is fast-acting and does not require attentional resources (Quillian, 1962; Collins & Loftus, 1975). Automatic processes contribute to semantic priming effects when the temporal window between the onsets of the prime and the target words is short (around 400 ms). In contrast, controlled mechanisms, including expectancy and post-lexical matching, are the result of attentional processes and reflect post-lexical semantic integration, being therefore slow and highly demanding of attentional capacity (Posner & Snyder, 1975; Becker 1976; Neely, 1977, 1991; Shiffrin & Schneider, 1977; Brown & Hagoort, 1993). Longer time intervals between prime and target words (> 400 ms) allow controlled processes to be activated.

Lexical-semantic organization has been also studied by measuring the N400, a negative ERP component, evoked in response to unrelated versus related word pairs, or to incongruent versus congruent terminal words in sentences. N400 amplitudes are shown to be more negative to target words (e.g., nurse) preceded by unrelated (e.g., bread) than by related (e.g., doctor) prime words (e.g., Kutas & Hillyard, 1980; Federmeier & Kutas, 1999; for a review, see Kutas & Federmeier, 2000). This is called the N400 semantic priming effect, and is suggested to reflect semantic integration both in linguistic and non-linguistic domains (for review, Kutas & Federmeier, 2011). Typically, it appears over the central-parietal recording sites (Bentin, McCarthy, & Wood, 1985), but its latency and distribution varies according to the modality of the stimulus presentation (e.g., Holcomb & Neville, 1990; Bentin et al., 1985; Kutas, Van Petten, & Besson, 1988; Van Petten & Luka, 2006).

Several studies investigated the contribution of automatic and controlled mechanisms to the N400 effect by using masked priming paradigms, by manipulating the proportion of related target words or the stimulus onset asynchrony (SOA) between the prime and the target words, or the direction of priming (forward *versus* backward) between words (e.g., Holcomb, 1988; Balota, Black, & Cheney, 1992; Anderson & Holcomb, 1995; Chwilla, Brown, & Hagoort, 1995; Deacon, Uhm, Ritter, Hewitt, & Dynowska, 1999; Silva-Pereyra, Harmony, Villanueva, et al., 1999; Brown, Hagoort, & Chwilla, 2000; Deacon, Hewitt, Yang, & Nagata, 2000; Hill, Strube, Roesch-Ely, & Weisbrod, 2002; Kiefer, 2002; Franklin, Dien, Neely, Huber, & Waterson, 2007). Overall, it has been suggested that both automatic activation and controlled processes underlie the N400 priming effect (e.g., Deacon et al., 2000; Kiefer, 2002; Silva-Pereyra et al., 1999; Chwilla, Hagoort, & Brown, 1998). Evidence for the support of automatic spreading activation has been shown in masked priming paradigms, where the N400 priming effects were obtained regardless of whether the words were masked or not, suggesting that the N400 reflects automatic spreading activation in the semantic network (Deacon et al., 2000; Kiefer, 2002). On the other hand, increasing the proportion of related word pairs within an experimental block increases the use of controlled processes related to expectancy: Indeed, the N400 effect was more pronounced in the high than in the low relatedness proportion lists (e.g., Holcomb, 1988; Chwilla et al., 1995; Brown et al., 2000). This suggests that even if automatic processes are involved in the N400 effect, controlled processes modulate its amplitude. In a complementary set of studies, different SOAs were used to manipulate automatic versus controlled processes (e.g., Anderson & Holcomb, 1995; Hill, Strube, Roesch-Ely, & Weisbrod, 2002; Hill, Ott, & Weisbrod, 2005). Automatic processes are engaged at short (< 400 ms) SOAs (Neely, 1977; De Groot, 1984), but decay over an extended time interval, which is when controlled processes are activated. Increasing the SOA length has been shown to augment the magnitude of the N400 component (Anderson & Holcomb, 1995; Hill et al., 2005), to modulate its distribution and timing (Anderson & Holcomb, 1995), or to have different effects depending on the ERP component (Hill et al., 2002; Franklin et al., 2007). In Hill et al. (2002), the N400 effect was obtained at both short and long SOAs, while a frontally distributed early negativity and a posteriorly distributed late component were found only at the short SOA.

1.2. Semantic priming and N400 effect in toddlers

In young children, there is evidence that the semantic system starts to develop during the second year of life. It has been shown that by 24-months of age, but not earlier, taxonomic and associative links between words are well established (e.g., Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009; Torkildsen et al., 2007; Arias-Trejo & Plunkett, 2013; Rämä et al., 2013). However, two recent studies showed that even 18-month-old children were sensitive to semantic relatedness between words (Rämä et al., 2013; Delle Luche et al., 2014). In a head turn preference procedure (HPP), children listened longer to word lists containing semantically related than to lists of unrelated words (Delle Luche et al., 2014). In an ERP study for spoken words, the N400 priming effect was obtained in 24-month-olds, and also in a subgroup of 18-month children with normal to high productive skills, which suggests that advanced productive vocabulary skills might contribute to the taxonomic organization of the developing lexical-semantic system (Rämä et al., 2013).

Moreover, an N400-like effect has been measured at very early stages of language acquisition, even before the development of lexical-semantic system, in cross-modal incongruence tasks using pictorial and linguistic stimuli (e.g., Friedrich & Friederici, 2004, 2005b, 2006, 2010). In some of these studies, the N400 effect has been obtained over the midline or right central-parietal recording sites (e.g., Friedrich & Friederici, 2005c, 2006; Rämä et al., 2013), while in others, the left hemisphere contributed more to the effect than the right (e.g., Friedrich & Friederici, 2004, 2005a; Torkildsen et al., 2006, 2007). The language-related ERPs have also shown to be more broadly distributed in younger than in older children (Mills et al., 1993, 1997; Friedrich & Friederici, 2005c). These variations in the distribution and laterality might be explained by the fact that the language-related ERPs are modulated according to several developmental factors during the first years of life, such as brain maturation (e.g., Friedrich & Friederici, 2010), improved vocabulary skills (e.g., Torkildsen et al., 2009; Mills et al., 1997, 2005), and language experience (bilingual versus monolingual; e.g., Conboy & Mills, 2006; Garcia-Sierra, Rivera-Gaxiola, Percaccio, Conboy, Romo, Klarman, Ortiz, & Kuhl, 2011). Still, the cognitive mechanisms underlying the priming effect in young children remain unspecified. Here, we explored whether automatic activation or controlled processes affect the magnitude of language-related ERPs in 18-month-old children by manipulating the SOA length between the prime and target words. Based on earlier assumptions in adult studies, the occurrence of semantic priming effects at a short SOA would indicate that automatic processes underlie semantic processing, while more pronounced priming effects at a long SOA would suggest that controlled processes are activated. There is also a possibility that automatic and controlled processes have different effects depending on the ERP component.

2. Material and Methods

2.1. Participants

Twenty 18-month-old (11 girls and 9 boys; range: 17 months and 4 days to 18 months and 25 days; mean 18 months and 8 days) children participated in the study. All children were monolingual French learners. Children were recruited from a database of parents who voluntarily participated in previous studies in child development in our laboratory and came from the Paris area. All children were born full-term and none of them suffered from hearing or language impairment. The parents were informed about the purpose of the study and gave informed consent before participating. An additional thirty-four children were tested but their data were rejected due to not being able to complete the experiment (n = 2) or insufficient number of trials (fewer than 10 trials) in each experimental condition (n = 32). The French translation of the MacArthur Communicative Development Inventory for Words and Sentences (CDI; Fenson, Dale, Reznick, Thal, Bates, & Hartung, 1993) was used to measure comprehensive and productive vocabulary size. The parents were asked to fill the inventory at home during the two weeks following the study. The inventory was returned for thirteen of the twenty children in our final sample. The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the University of Paris Descartes.

2.2. Stimuli

The stimuli were one-, two-, or three-syllable French nouns from eight different categories (animals, clothes, body parts, food, furniture, transportation, household items and nature). The words were presented in four different female voices to prevent children from relying on acoustic information during the priming task. Also, speaker variability has been shown to facilitate lexical neighbor learning in young children (Rost & McMurray, 2009). We chose 144 basic level words that were arranged into 48 related and 48 unrelated prime-target word pairs. Each target word was presented twice during the experiment. Related words were taxonomically, but not associatively related (e.g., elephant-bear) and unrelated words were not semantically or associatively related (e.g., plane-bear). 83% of the words were represented in the CDI and according to the English CDI norms they are produced by 29% of children at this age. The mean number of syllables was 2 for related (SD=1.78), unrelated (SD=1.68) and prime (SD=1.68) words. The mean number of phonemes was 4 (SD=4) for each word type. The mean durations were 649 ms, 663 ms and 669 ms for related, unrelated and target words, respectively. Paired sample t-tests did not yield significant differences between primes and targets for any of these three variables (all *ps* >0.05). The recordings were edited with Cool Edit 2000 (Syntrillium Software Corp., Phoenix, AZ) and normalized at 22 kHz sampling rate with Praat (5.3.02).

2.3. Procedure

Children were seated either by themselves on a small chair next to their parents or on their parents' laps in a dimly lit room at 140 cm from two loudspeakers from which sounds were delivered. Parents were instructed not to communicate verbally with their children during the experiment. Children had in front of them a small table with toys and crayons and were allowed to play or draw. No visual stimuli were presented during the experiment. Two stimulus onset asynchronies (SOA) were used, a short SOA of 1000 ms and a long SOA of 1600 ms. Each target word was presented twice, once preceded by a related and once preceded by an unrelated prime, and each trial was repeated in both SOA conditions. Presentation order of trials was randomized. The intertrial interval (ITI) was 2200 msec. Prime and target words in each trial were always spoken by a different speaker. The whole experiment lasted about 12 minutes.

2.4. Event-related potential recording and analyses

The electroencephalogram (EEG) was continuously recorded from 62 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0), filtered (band-pass = 0.1-100 Hz) and digitized (sampling rate = 250 Hz). During the recordings, the ERP electrodes were referenced to the vertex (Cz). Impedances were kept below 50 kΩ. Offline, the EEG was filtered (0.3-30 Hz) and segments of 800 ms from the word onset were averaged according to a 200-ms prestimulus baseline. Automated artifact rejection was conducted. The ocular artifact removal (OAR) algorithm was used to detect and remove eye blinks and eye movements (Gratton, Coles, & Donchin, 1983). Trials including artifacts exceeding ± 160 μV were rejected. Bad channels were replaced using spherical spline interpolation with the remaining channels. Segments with more than 20 bad channels were rejected. Epochs were averaged separately for each subject, target word type (related and unrelated), and SOA condition (short and long). The averaged segments were re-referenced to the average of left and right mastoids and, as a last step, baseline corrected. Epochs were grand-averaged across all participants for the target word type and SOA condition. A minimum of 10 artifact-free trials per word type and SOA condition were included in further analyses. The mean number of accepted trials was 16 (33%) for related (*SD*=5) and 17 (35%) for unrelated (*SD*=4) targets, at the short SOA, and 16 (33%) for related (*SD*=5) and 16 (33%) for unrelated (*SD*=5) targets at the long SOA. There were no significant differences in the number of trials between experimental conditions (all *p's* > .05).

2.5. Data analyses

The mean amplitudes of ERPs during the time windows of 150 to 350 ms (N2), 300 to 500 ms (N400), and 500 to 800 ms (LPN) were calculated. A repeated-measures analysis of variance (ANOVA) included trial type (related *versus* unrelated target word), SOA (short *versus* long), and hemisphere (left *versus* right) as within-subject factors, and vocabulary group (high *versus* low) as a between-subject factor. The mean amplitudes were calculated separately for each electrode in each time interval. In each recording area, the mean amplitudes extracted from eight (frontal sites) or ten (central-posterior site) electrodes were averaged. The midline electrodes were excluded from the statistical analyses, resulting in 36 channels in 4 regions of interest. The 36 channels with their equivalents according to the 10-10 international system of electrodes sites are as follow: 8, 9, 12, 13, 14, 15, 16, and 19 in left frontal, 1, 2, 3, 57, 58, 60, 61, and 62 in right frontal, 18, 22, 24, 25, 27, 28, 29, 31, 32, and 33 in left central-posterior, 41, 42, 43, 45, 46, 47, 48, 49, 50, and 52 in right central-posterior. According to the 10–10 international electrode position system, the electrode placements 13 and 62 in frontal area are approximately located around F3 and F4 positions, and placements 28 and 46 in parietal–occipital area around P3 and P4 positions (see Figs. 1A and 1B). The statistical analyses were conducted with SPSS (IBM SPP statistics, version 20) and the Greenhouse-Geisser correction was applied for non-sphericity when appropriate.

3. Results

From visual inspection of ERPs in response to target words, we observed more negative amplitudes for the unrelated than related target words at both frontal and the central-posterior recording sites, and both at the short and the long SOA. Two *2* (trial type) x *2* (SOA) x *2* (left and right hemispheres) ANOVAs were conducted at each recording sites to investigate whether the amplitudes were modulated by trial type and/or SOA.

Over the frontal recording sites, there was a significant main effect of trial type on the amplitudes of the N2 ($F(1,19) = 5.64$; $p = .028$). The mean amplitudes were significantly more negative for unrelated than for related target words ($t(19) = 2.38$; $p = .028$; $r = -.53$). Neither main effect of SOA ($F(1,19) = 0.53$; $p = .477$) nor interaction between trial type and SOA ($F(1,19) = .72$, $p = .407$) were significant. Still, when the trial effect was tested separately at the short (Fig. 1A) and the long (Fig. 1B) SOAs, the amplitudes were shown to be more negative for unrelated than for related target words at the long SOA ($t(19) = 2.23$, $p = .038$; $r = -.49$), but not at the short SOA ($t(19)=1.33$, $p = .198$).

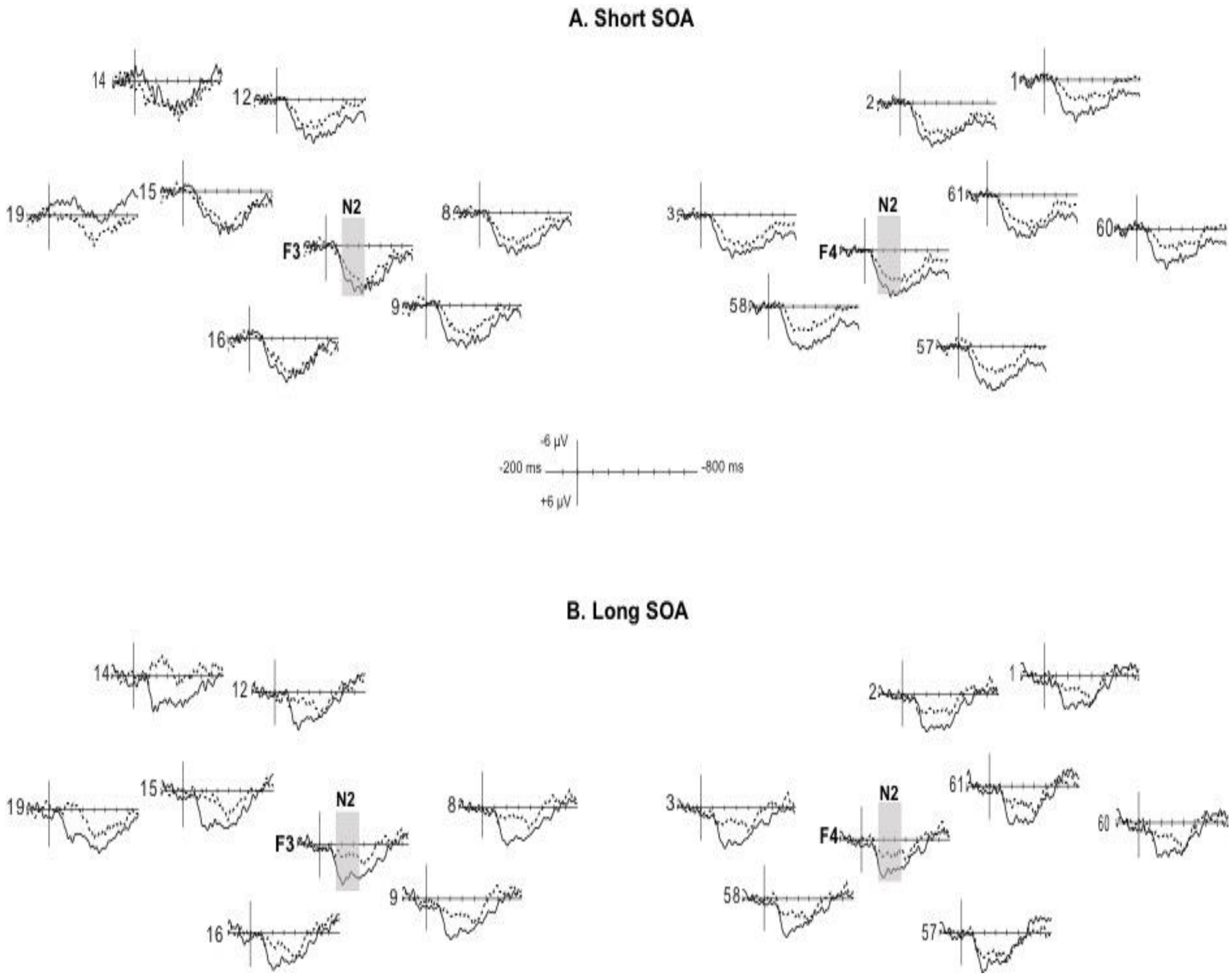


Figure 1. Grand-averaged waveforms for related (solid line) and unrelated (dashed line) target words at the short (**A**) and the long (**B**) SOAs over the frontal recording sites. The vertical lines illustrate the target word onset. The light grey box indicates the occurrence of the N2 component at F3 and F4 electrode positions.

Over the central-posterior recording sites (Fig. 2A and 2B), the main effect of trial type on the amplitudes of N400 was close to significance ($F(1,19) = 4.33$; $p = .051$). The mean amplitudes were more negative for unrelated (-.46 µV) than for related (1.82 µV) target words ($t(19) = 2.08$; $p = .051$; $r = -.46$). Neither the main effect of SOA ($F(1,19) = 2.22$; $p = .153$) nor the interaction between trial type and SOA were significant ($F(1,19) = .063$; $p = .805$).

The main effects of trial type ($F(1,19)= 2.67$; $p = .118$) and SOA ($F(1,19) = 2.42$; $p = .136$) on the amplitude of the LPN were not significant. But, a significant interaction between trial type, SOA, and hemisphere ($F(1,19) = 6.52$; $p = .019$) was found (Fig. 3). At the short SOA, the priming effect (unrelated *minus* related) was larger over the right (-3.40 µV) than the left (-.11 µV) recording sites ($t(19) = 1.95$, $p = .06$; $r = -0.43$), whereas at the long SOA, the priming effect was larger, though not significantly, over the left (-3.23 µV) than the right (-1.16 µV) recording sites ($t(19) = -1.22$, $p = .238$; $r = -.27$ (effect size)).

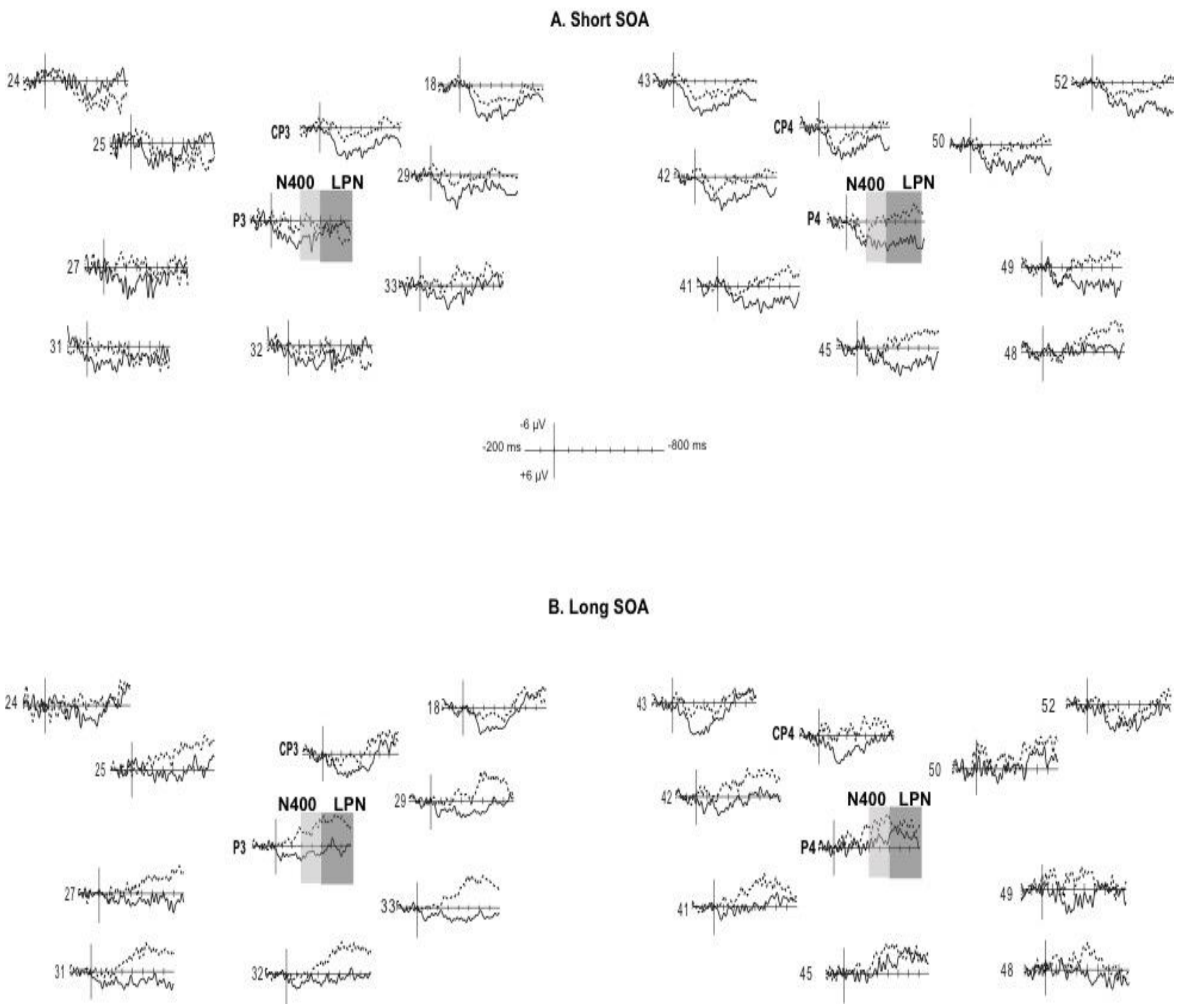


Figure 2. Grand-averaged waveforms for related (solid line) and unrelated (dashed line) target words at the short (**A**) and the long (**B**) SOAs over the central-posterior recording sites. The vertical lines illustrate the target word onset. The light and dark grey boxes indicate the occurrence of the N400 and LPN components, respectively, at P3 and P4 electrode positions.

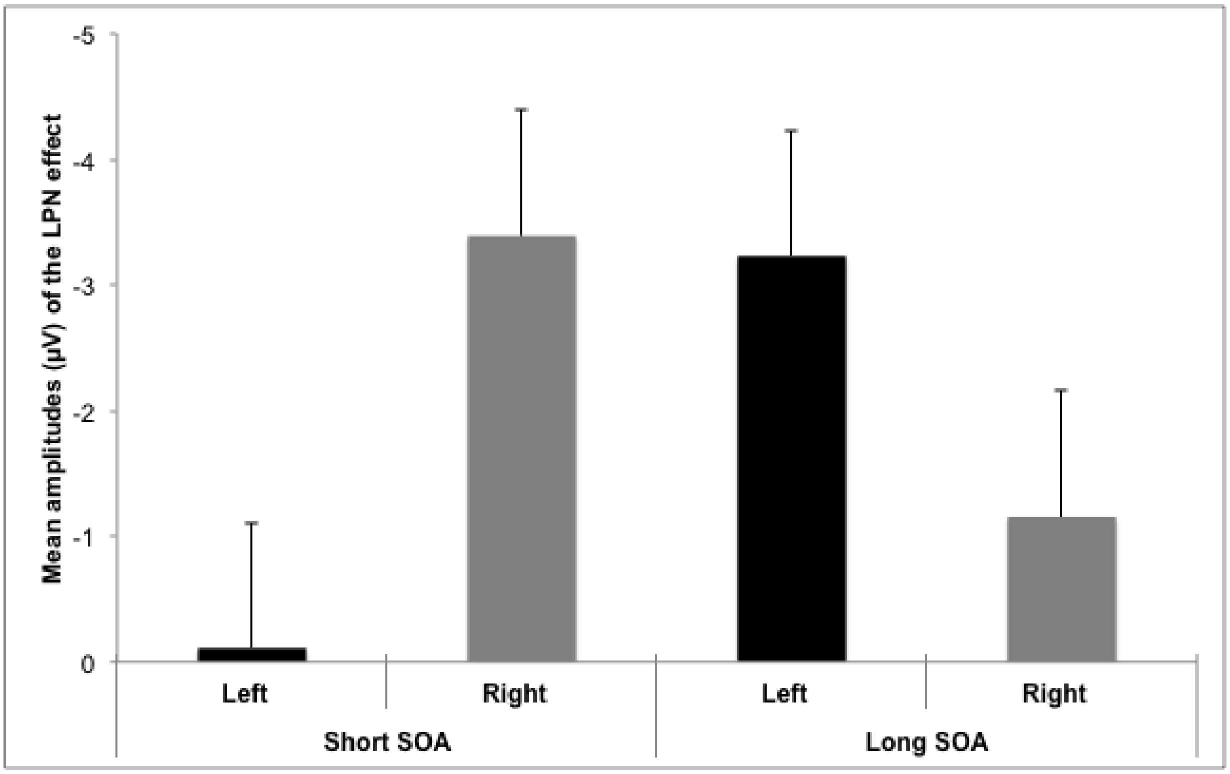


Figure 3. The magnitude of LPN effect (unrelated *minus* related target words) over the left and right central-posterior recording sites at each SOA. The vertical lines illustrate the standard error of means (SEM).

3.1. Productive Vocabulary size effect

Thirteen participants had the CDI filled with a mean of 23 words in production (*SD* = 11; range: 7 to 50 words). The median split (19 words) was used to divide the participants into two subgroups with normal-low and normal-high vocabulary sizes. The mean number of words produced in the normal-low producers (*n* = 7) group was 14 (*SD* = 5; range 7 to 18) and 30 in the normal-high (*n* = 6) producers group (*SD* = 10; range 19 to 50). We tested the interactions between trial type and productive vocabulary skills separately for each ERP component of interest. First, a significant interaction was found for the amplitudes of LPN ($F(1,11) = 5.92$; $p = .033$): In the normal-low producers, there was a trend to a significant trial type effect ($F(1,5) = 4.44$, $p = .089$), but not in the normal-high producers ($F(1,6) = 2.53$, $p = .163$). The interactions between trial type and productive vocabulary skills were not significant on the amplitudes of the N2 ($F(1,11) = .02$; $p = .898$), or the N400 ($F(1,11) = 4.52$; $p = .057$).

4. Discussion

In the present study, we investigated whether the SOA between the prime and the target word in a semantic priming task modulates the magnitudes of the language-related ERPs in children, with a specific emphasis on automatic or controlled processes contribution to these semantic priming effects. Children were exposed to related and unrelated spoken word pairs in two SOA conditions. Our results showed that the amplitudes of N2 and N400 components were more negative for unrelated than for related target words, confirming recent findings (Rämä et al., 2013; Delle Luche et al., 2014) that children at 18 months of age are sensitive to semantic relatedness between words. The amplitudes of the posteriorly distributed N400 component were not modulated by the SOA, whereas the amplitudes of the frontally distributed N2 component were larger at the long than at the short SOA, suggesting that controlled processes are engaged in the generation of the N2. Interestingly, the hemispheric distribution of late posterior negativity (LPN) was modulated by both trial type and SOA. At the short SOA, the priming effect was larger over the right hemisphere, whereas at the long SOA, the priming effect was larger over the left hemisphere.

Earlier, it has been shown in adults that the N400 effect is sensitive to both automatic activation and controlled processes but its magnitude is augmented at longer SOAs when controlled processes are engaged (Anderson & Holcomb, 1995; Hill et al., 2005). In our study, the magnitude of N2 component was augmented at the longer SOA while the N400 was insensitive to SOA length. The N2 (or N200-400) component has earlier been associated with word comprehension or familiarity (Mills et al., 1993, 1997; Thierry, Vihman, Roberts, 2003), correct word pronunciations (Mills, Prat, Zangl, Stager, Neville, & Werker, 2004), and processing of novel object-word pairings (Mills et al., 2005). It has been interpreted as an index of automatic orientation of attention to (low probability) recognizable words (Thierry et al., 2003) or processing of word meaning (Mills et al., 1993, 2005). Our results further suggest that the N2 is also associated with the engagement of controlled processes during processing of word meaning in young children.

The SOA-dependent effects in adults were also shown to vary according to the modality of the stimulus presentation. Simultaneous or overlapping word presentations abolishes the N400 effect for aurally, but not for visually presented words, while at a longer SOA, the effect is obtained also in the auditory modality, thus suggesting that spoken word processing might be more sensitive to controlled processes (Anderson & Holcomb, 1995). The distribution of the N400 effect in short and long SOA conditions has shown to be similar among adults (e.g., Deacon et al., 1999; Hill et al., 2002), and the effect has been mostly found over the central and parietal (e.g., Holcomb & Neville, 1990; Anderson & Holcomb, 1995) and the midline and the right recording sites (e.g., Rossel, Price, & Nobre, 2003). In children, the distribution and the lateralization of language-related ERPs has been shown to vary across studies (e.g., Mills et al., 1993, 2004, 2005; Torkildsen et al., 2006, 2007; Friedrich & Fridherici, 2004, 2005a, 2005b). For example, the N400 effect in priming and picture-word congruence tasks has been found over the left and the right hemispheres (Friedrich & Friederici, 2004, 2005a, 2005c, 2006; Torkildsen et al., 2006, 2007, 2009; Rämä et al., 2013), and the right-hemispheric distribution in picture-word congruence tasks has also been linked with higher vocabulary skills (Friedrich & Friederici, 2004). In contrast, the N2 effect - associated with word comprehension - has been seen in broad distributions over anterior and posterior recording sites in younger children, while in older children, the component was larger over the left temporal and parietal recoding sites (Mills et al., 1993, 1997). Moreover, the left hemispheric bias for word comprehension in older toddlers has also been shown to correlate with the increased vocabulary skills (Mills et al., 1993, 2005). Interestingly, in the current study, the magnitude of the LPN effect was similar at both SOA conditions, while the lateralization of the effect differed, being more prominent over the left hemisphere at the long SOA, and more prominent over the right hemisphere at the short SOA. A similar late negativity, continuing beyond the classical N400 window, has been observed in earlier developmental studies and it has been suggested to indicate slower semantic processing in young children (e.g., Friedrich & Friederici, 2004; Torkildsen et al., 2007). Our findings further suggest that automatic activation of word meanings contributes to the right-lateralized effects, while effects linked to controlled processes appear over the posterior left hemisphere. This preliminary suggestion needs, however, further study to be confirmed.

Both short and long SOAs used in our study are relatively long, as SOAs used in previous adult studies are much shorter (around 200 ms for a short SOA, and around 800 ms for a long SOA). Thus, we cannot rule out the possibility that controlled processes were already engaged at our short SOA condition, and instead of manipulating automatic and controlled processes, we manipulated working memory or more general cognitive load in our two SOA conditions. To our knowledge, there is only one study using the primed intermodal preferential looking (IPL) task that explored the effect of the SOA length (200 ms *versus* 400 ms) on semantic priming in 18- and 24-month-old children (Styles & Plunkett, 2009). In the primed IPL paradigm, children heard a carrier phrase containing a prime word (e.g., “yesterday I bought a *cat*”) followed by an isolated target word, either semantically related (e.g., dog) or unrelated (e.g., plate) to the prime word. A pair of images, illustrating the named target and a distracter object, appeared on the screen at a SOA of 200 ms or 400 ms from the onset of the spoken target word. Priming effect was expressed by an increased looking time at the named target when it was preceded by a semantically related than by unrelated prime word. The results of Styles and Plunkett showed that priming effects were not influenced by SOA length. Even though the authors did not discuss the underlying mechanisms of such rapid priming, it might be assumed that automatic activation processes were engaged during target word recognition. In ERP studies, short (500 ms), intermediate (900 to 1200 ms) (Torkildsen et al., 2007; Kuipers & Thierry, 2012; Rämä et al., 2013) and long (1800 ms) (e.g., Friedrich & Friederici, 2004; Torkildsen et al., 2006) SOAs have been used. As was shown in adults' studies, simultaneous presentation of spoken word pairs abolishes priming effects due to the lack of time for the prime processing (e.g., Anderson & Holcomb, 1995). Thus, in our study, we chose to use relatively long SOAs to avoid an overlap between words, as the shortest SOA between prime and target words could not be shorter than the duration of the longest words. Furthermore, the speed of word processing is slower in young children than in adults (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998) and the N400 response was shown to last longer in children than in adult participants (e.g., Friedrich & Friederici, 2004, 2005c), suggesting that automatic processes might not decay as fast as in adults, and that longer time is needed for the controlled processes to be engaged in young children. However, another question is whether attentive mechanisms required in the engagement of controlled processes are already developed at the age of 18-months. Manipulating both SOA and the proportion of related word pairs in the experiment could empirically test this question. It was earlier shown in adult studies that increasing the proportion of related word pairs within an experimental block increases the involvement of controlled processes. Participants generate expectancy from the prime to the related target word and tend to pay greater attention to related word pairs. If children exhibited priming effect for the high relatedness proportion block at long SOA, but not at short SOA, it would indicate that controlled processes related to expectancy are already developed.

Here, the amplitudes of the LPN interacted with productive vocabulary skills, whereas the amplitudes of N2 and N400 did not. In our earlier study, the N400 effect was obtained only in those 18-month-olds who had normal-to-high productive vocabulary skills (Rämä et al., 2013), whereas in the present study, the N400 effect was obtained in the normal-low producers but not in the normal-high producers. In the current study, all participants produced fewer than 50 words (0 to 50 words), indicating that they were still at the start of the vocabulary spurt, whereas in our earlier study (Rämä et al., 2013), the range of words produced by all participants was much larger (0 to 214 produced words) with a mean of 78 words in the normal to high producers. Accordingly, we consider that participants in the present study had not yet entered the phase of accelerated vocabulary learning, which might explain the absence of interaction between the N400 amplitude and the vocabulary skills. Nevertheless, the 18-month-olds, even with fewer than 50 words in their productive vocabulary, were sensitive to taxonomic relations, suggesting that the semantic links between words are already established by that age.

Conclusions

Altogether, our results suggest that even before entering the vocabulary spurt, words are organized by their semantic relatedness in the mental lexicon of an 18-month-old. The occurrence of the N400 effect over the central-parietal recording sites in both SOA conditions suggests that both automatic and controlled processes are activated during auditory priming. The N2 was modulated by the SOA length, suggesting that engagement of controlled processes contribute to this frontally distributed early negativity. Inter-hemispheric difference for the amplitudes of LPN across conditions further indicate that even though both processes underlie priming at this age, the neural resources generating them might be different. Language-related ERPs in developing brain are shown to be modulated by several neural and cognitive developmental factors such as brain maturation, existence of established and specified lexical–semantic memory representations, vocabulary skills, or language experience (e.g., Friedrich & Friederici, 2010; Mills et al., 1997, 2005). Our study further suggests that language-related ERPs are modulated depending on whether automatic or controlled processes are engaged during word processing.

Acknowledgement

We thank all families for participating and contributing to this research. This work was funded by Sorbonne Paris Cité Grant.

References

Anderson, J.E., & Holcomb, P.J. (1995). Auditory and visual semantic priming using different stimulus onset asynchronies: An event-related brain potential study. *Psychophysiology, 32*, 177-190.

Arias-Trejo, N., & Plunkett. K. (2009). Lexical–semantic priming effects during infancy. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364* (1536), 3633–3647.

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.

Balota, D.A., Black, S.R, & Cheney, M. (1992). Automatic and attentional priming in young and older adults: reevaluation of the two-process model. *Journal of Experimental Psychology: Human Perception and Performance, 18* (2), 485-502.

Becker, C.A. (1976). Allocation of attention during visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 556-566.

Bentin, S., McCarthy, G., & Wood, C.C. 1985. Event-related potentials, lexical decision and semantic priming. *Electroencephalography and Clinical Neurophysiology, 60*, 343-355.

Brown, C.M., Hagoort, P., & Chwilla, D.J. (2000). An event-related brain potential analysis of visual word priming effects. *Brain and Language, 72*, 158-190.

Brown, C.M., & Hagoort, P. (1993). The processing nature of the N400: evidence from masked priming. *Journal of Cognitive Neuroscience*, *5* (1), 34-44.

Chwilla, D.J., Brown, C.M., & Hagoort, P. (1995). The N400 as a function of the level of processing. *Psychophysiology*, *32*, 274-285.

Chwilla, D. J., Hagoort, P., & Brown, C. M. (1998). The mechanism underlying backward priming in a lexical decision task: Spreading activation versus semantic matching. *The Quarterly Journal of Experimental Psychology: Section A*, *51*(3), 531-560.

Collins, A.M., & Loftus, E.F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, *82*, 407-428.

Conboy, B.T., & Mills, D. (2006). Two languages, one developing brain: event-related potentials to words in bilingual toddlers. *Developmental Science*, *9* (1), 1-12.

Deacon, D., Uhm, T.J., Ritter, W., Hewitt, S., & Dynowska, A. (1999). The lifetime of automatic semantic priming effects may exceed two seconds. *Cognitive Brain Research, 7,* 465-472.

Deacon, D., Hewitt, S., Yang, C. M., & Nagata, M. (2000). Event-related potential indices of semantic priming using masked and unmasked words: evidence that the N400 does not reflect a post-lexical process. *Cognitive Brain Research*, *9*(2), 137-146.

De Groot, A. (1984). Primed lexical decision: combined effects of the proportion of related prime-target and the stimulus onset asynchrony of the prime and target. *The Quarterly Journal of Experimental Psychology*, *36A* (2), 253-280.

Delle Luche, C., Durrant, S., Floccia, C., & Plunkett, K. (2014). Implicit meaning in 18-month-old toddlers. *Developmental Science,* 1-8.

Federmeier, K.D., & Kutas, M. (1999). A rose by any other name: long-term memory structure and sentence processing. *Journal of Memory and Language, 41*, 469-495.

Fenson, L., Dale, P., Reznick, S., Thal, D., Bates, E., Hartung, J., Pethick, S., & Reilly, J. (1993). *MacArthur Communicative Development Inventories: User's guide and technical manual*. San Diego, CA: Singular Publishing Group.

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* (3), 228-231.

Franklin, M. S., Dien, J., Neely, J. H., Huber, E., & Waterson, L. D. (2007). Semantic priming modulates the N400, N300, and N400RP. *Clinical Neurophysiology, 118*(5), 1053-1068.

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,* 1465-1477.

Friedrich, M., & Friederici, A.D. (2005a). Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. *NeuroReport, 16* (6), 653-656.

Friedrich, M., & Friederici, A.D. (2005b). Phonotactic knowledge and lexical-semantic processing in one-year-olds: brain responses to words and nonsense words in picture contexts. *Journal of Cognitive Neuroscience, 17*, 1785-1802.

Friedrich, M., & Friederici, A.D. (2005c). Semantic sentence processing reflected in the event-related potentials of one- and two-year-old children. *NeuroReport, 16* (16), 1801-1804.

Friedrich, M., & Friederici, A.D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43*, 1-12.

Friedrich, M., & Friederici, A.D. (2010). Maturing brain mechanisms and developing behavioral language skills. *Brain and Language, 114*, 66-71.

Garcia-Sierra, A., Rivera-Gaxiola, M., Percaccio, C.R., Conboy, B.T., Romo, H., Klarman, L., Ortiz, S., & Kuhl, P.K. (2011). Bilingual language learning: an ERP study relating early brain responses to speech, language input, and later word production. *Journal of Phonetics, 39* (4), 546-557.

Graton, G., Coles, M.G.H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalograohy & Clinical Neurophysiology, 55*, 468-484.

Hill, H., Strube, M., Roesch-Ely, D., & Weisbrod, M. (2002). Automatic vs. Controlled processes in semantic priming – differentiation by event-related potentials. *International Journal of Psychophysiology, 44*, 197-218.

Hill, H., Ott, F., & Weisbrod, M. (2005). SOA-dependent N400 and P300 semantic priming effects using pseudowords and a delayed lexical decision. *International Journal of Psychophysiology, 56* (3), 209-221.

Holcomb, P.J. (1988). Automatic and attentional processing: an event-related brain potential analysis of semantic priming. *Brain and Language, 35* (1), 66-85.

Holcomb, P.J., & Neville, H.J. (1990). Auditory and visual semantic priming in lexical decision: a comparison using event-related brain potentials. *Language and Cognitive Processes, 5*, 281-312.

Kiefer, M. (2002). The N400 is modulated by unconsciously perceived masked words: Further evidence for an automatic spreading activation account of N400 priming effects. *Cognitive Brain Research*, *13*(1), 27-39.

Kuipers, J.R., & Thierry, G. (2012). Event-related potential correlates of language change detection in bilingual toddlers. *Developmental Cognitive Neuroscience, 2* (1), 97-102.

Kutas, M., & Federmeier, K.D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences, 4* (12), 463-470.

Kutas, M., & Federmeier, K.D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62*, 621-647.

Kutas, M., & Hillyrad, S.A. (1989). An electrophysiological probe of incidental semantic association. *Journal of Cognitive Neuroscience, 1*, 38-49.

Kutas, M., & Hillyard, S.A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*, 203-205.

Kutas, M., van Petten, C., & Besson, M. (1988). Event-related potential asymmetries during the reading of sentences. *Electroencephalography and Clinical Neurophysiology, 69*, 218-233.

Lucas, M. (2000). Semantic priming without association: a meat-analytic review. *Psychonomic Bulletin & Review, 7*, 618-630.

Meyer, D.E., & Schvaneveldt, R.W. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90*, 227-234.

Mills, D.L., Coffey-Corina, S.A., & Neville, H. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *Journal of Cognitive Neuroscience, 5* (3), 317-334.

Mills, D.L., Coffey-Corina, S., Neville, H.J. (1997). Language comprehension and cerebral specialization from 13 to 20 months. *Developmental Neuropsychology, 13* (3), 397-445.

Mills, D.L., Prat, C., Zangl, R., Stager, C.L., Neville, H.J., & Werker, J.F. (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.

Mills, D.L., Plunkett, K., Prat, C., & Schafer, G. (2005). Watching the infant brain learn words: effect of vocabulary size and experience. *Cognitive Development, 20* (1), 19-31.

Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General, 106* (3), 226-254.

Neely, J.H. (1991). Semantic priming effects in visual word recognition: a selective review of current findings and theories. In: Besner, D., Humphreys, G.W. (Eds), Basic progress in Reading – Visual Word Recognition. Erlbaum, Hillsdale, NJ, pp. 264-333.

Neely, J.H., & Keefe, D.E. (1989). Semantic context effects on visual word processing: a hybrid prospective-retrospective processing theory. In G.H. Bower (Ed.), The psychology of learning and motivation: Advances in research and theory, pp. 207-248. New York: Academic.

Neely, J.H., Keefe, D.E., & Ross, K.L. (1989). Semantic priming in the lexical decision rask: roles of prospective prime-generated expectancies and retrospective semantic matching. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 1003-1019.

Posner, M.I., Snyder, C.R.R. (1975). Attention and Cognitive control. In: Solso, R.L. (Ed.), Information Progressing and Cognition: The Loyota Symposium. Erlbaum, Hillsdale, NJ, pp. 55-85.

Quillian, M.R. (1962). A revised design for an understanding machine. *Mechanical Translation, 7*, 17-29.

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*, 1-10.

Rost, G.C., & McMurray, B. (2009). Speaker variability augments phonological processing in early word processing. *Developmental Science, 12* (2), 339-349.

Shiffrin, R.M., & Schneider, W. (1977). Controlled and automatic human information processing: perceptual learning, automatic attending, & a general theory. *Psychological Review, 84* (2), 127-190.

Silva-Pereyra, J., Harmony, T., Villanueva, G., Fernandez, T., Rodriguez, M., Galan, L., Diaz-Comas, L., Bernal, J., Fernandez-Bouzas, A., Marosi, E., Reyes, A. (1999). N400 and lexical decisions: automatic or controlled processing? *Clinical Neurophysiology, 110*, 813-824.

Styles, S. J., & Plunkett, K. (2009). How do infants build a semantic system? *Language and Cognition, 1* (1), 1–24.

Thierry, G., Vihman, M., & Roberts, M. (2003). Familiar words capture the attention of 11-month-olds in less than 250 ms. *NeuroReport, 14* (18), 2307-2310.

Torkildsen, J. vK., Hansen, H.F., Svangstu, J.M., Smith, L., Simonsen, H.G., Moen, I., & Lindgren, M. (2009). Brain dynamics of word familiarization in 20-month-olds: effects of productive vocabulary size. *Brain and Language, 108* (2), 73-88.

Torkildsen, J. vK., 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.

Torkildsen, J. vK., Syversen, G., Simonsen, H.G., Moen, I., & Lindgren, M. (2007). Electrophysiological correlates of auditory semantic priming in 24-month-olds. *Brain and Language, 20* (4), 332-351.

Van Petten, C., & Luka, B.J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and Language, 97*, 279-293.

[Study III: In preparation]

Semantic similarity effects during word recognition in 24-month-old toddlers

Louah Sirri [1], Andrea Helo [1, 2], Pia Rämä [1, 3]

[1]Université Paris Descartes, Sorbonne Paris Cité, Paris, France

[2] Escuela de Fonoaudiología, Universidad de Chile, Santiago, Chile

[3] CNRS, Laboratoire Psychologie de la Perception (UMR 8242), Paris, France

[5836 Words]

Corresponding author:

Louah Sirri

Laboratoire Psychologie de la Perception (CNRS, UMR 8242)

Université Paris Descartes

45, rue des Saints-Pères

75006 Paris

France

E-mail: louah.sirri@parisdescartes.fr

Fax : +33 (0) 1 42 86 33 22

Tel : +33 (0) 1 42 86 43 20

Highlights

- Semantic competitor interferes with word recognition in 24-month-olds
- The amount of interference depends on semantic similarity between items
- Distant semantic neighbors interfere less than close semantic neighbors
- Productive vocabulary skills contribute to interference effect

Abstract

We investigated whether the presence of a semantic competitor in a looking while listening (LWL) task affects word recognition in 24-month-old toddlers. Children were presented with pairs of images, a target and a competitor, illustrating objects or animals sharing different amount of overlapping semantic features. Three experimental conditions were created in which paired images illustrated items that were either semantically near (e.g., plate-bowl) or distant (e.g., plate-fork) competitors, or unrelated (e.g., plate-sheep). After a preview of the images, a spoken word was delivered and looking times were recorded during the whole trial. Our results showed that the likelihood of fixating the competitor was affected by the degree of its semantic feature similarity to the target. Children looked longer at the named target in the unrelated than in the distant condition. In the near condition, looking times were equally distributed among target and distracter images. Across time, the differences in target looking proportions between distant and unrelated conditions were observed earlier than between near and distant conditions. These results suggest that in taxonomic categories words are organized according to semantic similarity distances, reflecting graded organization.

Keywords: word recognition, lexical-semantic organization, semantic similarity, and language development

Introduction

During their second year of life, children express a dramatic improvement in their linguistic skills due to an accelerated rate of word learning and producing (e.g., Bloom, 1973; Bloom & Markson, 1998; for a review, see Ganger & Brent, 2004). Furthermore, it has been shown that over that period, children make striking gains in speed and efficiency in recognizing familiar words and by 2 years of age, they progress rapidly towards an adults-like pattern of language processing (e.g., Fernald et al., 1998; Swingley, Pinto, & Fernald, 1999; Fernald, Swingley & Pinto, 2001; Swingley & Fernald, 2002; Bergelson & Swingley, 2013). Word recognition has been investigated by using intermodal preferential looking (IPL) and looking while listening (LWL) paradigms where children look at pairs of images while listening to speech naming one of the images, and their eye-movements and looking times are monitored (e.g., Golinkoff, Hirsh-Pasek, Cauley & Gordon, 1987; Reznick, 1990; Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Fernald, Zangl, Portillo, & Marchman, 2008). For example, children hear '*where's the_?'* while looking at two images illustrating the target (e.g., doggie) and distracter (e.g., shoe) items. The results of Fernald et al. (1998) revealed that all children look at the named target item, but differences in speed of processing were found between the age groups studied. At 24- and 18-months, children were faster than 15-month-olds in shifting their looking from the distracter to the named target picture. In the youngest group, children did not shift their gaze to the target image until the end of the spoken word. In a following study, 18-month-old children were shown to recognize words even when only partial acoustic information is presented (Fernald et al., 2001). Moreover, children's expressive skills over the second year were shown to contribute to the efficiency and speed of word recognition (Fernald, Perfors, & Marchman, 2006). The findings of this longitudinal study demonstrated that at 25-months, children who were faster in recognizing familiar words were those children who displayed an accelerated increase in productive vocabulary during the second year of life (e.g., 15-, 18-, and 21-months). The authors also suggested that the interaction between age, speed of processing, and vocabulary growth factors enable children to establish better lexical representations and access words as meaningful items. Furthermore, it has been demonstrated that speed of processing and vocabulary skills are strongly correlated to cognitive abilities later in childhood, mainly to the working memory (Marchman & Fernald, 2009). Yet, even less is known about the developing lexical-semantic system and the question of whether newly acquired words are related to each other and integrated into interconnected lexical-semantic system is under-investigated.

Recently, this question has been studied by using primed IPL task (Arias-Trejo & Plunkett, 2009, 2013; Styles & Plunkett, 2009), head turn preference procedure (HPP; Willits, Wojcik, Seidenberg, & Saffran, 2013; Delle Luche, Durrant, Floccia, & Plunkett, 2014), and by using the event-related potential (ERP) technique (Torkildsen Sannerud, Thormodsen, Syversen, Simonsen, Moen, Smith, & Lindgren, 2006, 2007; Rämä, Sirri, & Serres, 2013; Sirri & Rämä, 2015). In the primed IPL task, children hear a carrier phrase containing a prime word (e.g., "yesterday I saw a *cat*") followed by an isolated target word, either semantically related (e.g., dog) or unrelated (e.g., plate) to the prime word. A few hundred milliseconds after the target word onset, a pair of images, composed of the named target and a distracter, appears on the screen and target looking time is measured. The priming effect is expressed by an increased looking time at the named target when it is preceded by a semantically related prime word as opposed to when it is preceded by an unrelated prime word. In primed IPL tasks, the target and distracter image are semantically unrelated and do not overlap phonologically or perceptually. It has been demonstrated that at 24-months of age, children were sensitive to different semantic relationships, such associative and/or taxonomic, between lexical items (Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2013;

Johnson, McQueen, & Huettig, 2011). A priming effect was obtained also when prime and target words were associatively related but drawn from different taxonomic categories (e.g., carrot - bunny), or both taxonomically and associatively related (e.g., cat - dog) (Arias-Trejo & Plunkett, 2013). At 21-month-olds, a priming effect was found only for taxonomically and associatively related word pairs (Arias-Trejo & Plunkett, 2009). In addition, 18-month-olds exhibited systematic looking to the named target, but irrespective of the semantic relationship to the preceding prime, indicating that they were not yet sensitive to priming (Arias-Trejo & Plunkett, 2009; Styles & Plunkett, 2009). However, the authors argued that the absence of priming effects at this age might be due slower speech processing or to lack of associative strength between stimuli used. Another alternative is that the cross-modal priming tasks might be too demanding in terms of attentional capacities since children are to process stimuli in two different modalities (visual and auditory) simultaneously. In a recent HPP study, demonstrating that 18-month-old children listened longer to lists containing semantically related words as opposed to lists containing semantically unrelated words (Delle Luche et al., 2014). This finding suggests that at 18-months, there is a sensitivity to semantic relationships between words. In event-related potential (ERP) studies with children, the N400 component (an index of semantic violations; for a review, see Kutas & Federmeier, 2011). was obtained at 20-months in response to incongruent picture-word pairs (e.g., Torkildsen, 2006), at 24-months (Torkildsen et al., 2007; Rämä et al., 2013) and at 18-months for taxonomically unrelated spoken words (Sirri & Rämä, 2015).

Taken together, these findings demonstrate that associative and/or taxonomic relationships might underpin the lexical-semantic structure (e.g., Arias-Trejo & Plunkett, 2009, 2013; Styles & Plunkett, 2009; Rämä, et al., 2013; Delle Luche, et al., 2014). In addition, 24-month-old children are able to process taxonomically related items even when the target object is not labelled

(Johnson, McQueen, & Huettig, 2011) and even in the absence of any visual support (e.g., Willits et al., 2013). Nevertheless, in the above-mentioned studies, the target and the distracter images were systematically unrelated and the semantic similarity distances between the two items were not manipulated. Semantic similarity reflects the distances between lexical items based on their shared meanings and features overlap (e.g., categorical, perceptual, functional). That is, to which extent two lexical items have features in common. Thus, whether the developing lexical-semantic system is organized according to taxonomic relationships and to features overlap is a question of great interest for it provides further evidence about how children group words into semantic categories. Earlier, it has been argued that objects belonging to the same category share often perceptual features and that children overextend known words based on 'shape' bias (e.g., Clarck, 1973; Thomson & Chapman, 1977).

A few recent studies investigated the effect of perceptual knowledge (e.g., shape or colour) and semantic similarity on word recognition during language development. It has been shown that upon hearing the word '*strawberry*', 36- and 24-month-old children tend to look longer a red object, suggesting by that age, a prototype of the object's perceptual aspects is already established (Johnson et al., 2011). Moreover, word recognition was shown to be affected by the simultaneous presentation of categorical and perceptual similar competitors (Arias-Trejo & Plunkett, 2010). In this study, four experimental conditions were manipulated, during which 18-, 21- and 24-month-old children were presented with paired images drawn from different semantic categories and perceptually dissimilar (e.g., duck-bike) or similar (e.g., apple-ball), and drawn from the same semantic category and perceptually dissimilar (e.g., dog-fish) or similar (e.g., cow-horse). The results showed, at all ages, increased looking times to the named target in all conditions, except when items were categorically and perceptually similar where looking times were equally distributed among the competitor and target images. These results suggest that simultaneous presentation of target-competitor objects that are both taxonomically related and perceptually similar disrupts target word recognition. The authors also suggested that even at young age as 18-months, lexical-semantic organization reflects adults' lexical processing. However, whether lexical-semantic organization based on features overlap is a continuous process during language development, is a question to clarify.

In the current study, we investigated whether semantic similarity, based on adult norms, between target and competitor items interferes with the target word recognition. In the previously mentioned behavioural tasks, semantic priming was studied by manipulating the semantic relatedness between the spoken prime and target word. We rather opted to study word recognition by manipulating the semantic similarity between the named target and the competitor images. By doing so, our goal was to explore whether near semantic competitor interferes more with the target word recognition than distant or unrelated competitor, reflecting thus a graded semantic organization in the developing lexicon. In adults, semantic similarity effects during word recognition have been investigated by using the visual world paradigm (VWP), which is considered as a sensitive tool to detect even small similarity effects, sometimes not observed in lexical decision tasks (for review, see Huettig, Rommers, & Meyer, 2011). In VWP, participants typically hear a spoken word while looking at a visual display containing several objects and they are instructed to click or point out on the target object. If one of the objects (e.g., lock) illustrated in the display is semantically related to the spoken target word (e.g., key), participants tend to look longer at the related than at the unrelated (e.g., deer) object (Huettig & Altmann, 2004, 2005; Yee & Sedivy, 2006; Yee, Overtone, Thompson-Schill, 2009). Interestingly, when the competitor images were presented simultaneously with the target image (e.g., cake) and illustrated either near (e.g., pie), distant (e.g. pear) or unrelated (e.g., stone) concepts, looking times to competitors reflected a graded semantic competition. That is, fixations to near competitors were greater than to distant and unrelated competitors. Also, fixations to distant competitors were greater than to unrelated competitors (e.g., Huettig & Altmann, 2005; Mirman & Magnuson, 2009). These findings indicate that the likelihood of fixating a competitor object is predicted by the amount of feature similarities shared with the target concept, suggesting that the semantic system is organized by similarity distances rather than by categorical relations (Mirman & Magnuson, 2008, 2009).

Here, we explored how semantic similarity affects word recognition. Children were presented with two images on a visual display - a target and a competitor – illustrating either concepts that were near (e.g., cow - sheep) or distant (e.g., cow - deer) competitors from the same taxonomic category, or unrelated concepts drawn from different taxonomic categories (e.g., cow - fork). The items were chosen from adults' feature norms (McRae, Cree, Seidenberg, & McNorgan, 2005). We hypothesized that, if the developing lexical-semantic system is organized by semantic similarity distances, the likelihood of fixating the competitor will depend on the amount of its semantic similarity with the target. That is, target looking would reflect graded similarity effects. Near semantic competitors would be strongly activated and interfere with the target word recognition. Distant competitors would be activated more than unrelated competitors but less than near competitors. On the other hand, increased target looking times only in the unrelated condition would indicate that the developing lexical-semantic system is organized by taxonomic categories and not by similarity distances. Since in earlier LWL tasks expressive skills were shown to contribute to the speed and efficiency of word recognition, we hypothesize that productive vocabulary skills affect to target looking times differently in each experimental condition, suggesting further that vocabulary size contribute to the graded lexical-semantic organization.

Methods

Participants

Thirty 24-month-old French learning monolingual children (15 girls and 15 boys; mean age: 24 months and 17 days, range: 23 months and 21 days – 25 months and 5 days) participated to the experiment. An additional three children participated, but were not included in the final sample because of their failure to pay attention to more than 50% of trials (n=2) or because they had less than 50% of trials after the data analysis, in each of the experimental conditions (n=1). Children were recruited from a database of parents who voluntarily participated in previous studies in child development in our laboratory and came from the Paris area. All children were born full-term and had no known hearing or visual problems and none of them suffered from language impairment. The parents were informed about the purpose of the study and gave informed consent before participating. The French translation and adaptation of the MacArthur Communicative Development Inventory for Words (CDI) was used to measure each subject's comprehensive and productive vocabulary size (Fenson, Dale, Reznick, Thal, Bates, & Hartung, 1993). The parents were asked to fill the CDI within the following two weeks of the experiment. The inventory was returned for twenty-three of the thirty children in our final sample. The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the University of Paris Descartes.

Stimuli

Sixteen images, illustrating common objects or animals (see **Table I**.), from four different superordinate categories (animals, clothes, food and household items) were arranged in 24 pairs of target and distracter images (Appendix I). Each image was presented three times during the experiment, once in each of the three experimental conditions (near, distant and unrelated). The amount of feature similarities between the concepts illustrated in two images was different across the conditions. The similarity distance measures were taken from the shared perceptual features norms (McRae et al., 2005). The norms were based on responses given by 30 adult participants that listed 10 features for each of 541 living and non-living basic-level concepts. The feature similarities were obtained by calculating the cosine between each pair of concepts. The cosine provides a distance measure reflecting similarity in features between the target and the competitor, and it ranges from -1 (opposite vectors) to 1 (identical vectors), with 0 indicating independent vectors. In our study, the cosines between near competitors were closer to 1 (mean: 0.520; SD=0.045) than in the distant (mean: 0.236; SD=0.093) and unrelated (mean: 0.016; SD=0.032) competitors. We also conducted a target-competitor similarity test with adults. Sixteen participants (mean age: 25 years old; range: 19 to 36 years) were asked to rate on a 7-point scale (from 1=*dissimilar* to 7=*highly similar*) the visual similarity of the 24 target-competitor pairs, in terms of colour, shape, and surface texture. Trial order was randomized. The mean ratings were 4.2 (SD=0.81) for near, 2.6 (SD=0.55) for distant, and 1.3 (SD=0.33) for unrelated pairings. The mean values were significantly higher for near than for distant pairings ($t(15)=10.96$, $p<.001$) and for distant than for unrelated pairings ($t(15)=8.46$, $p<.001$). Only distant ($t(15)=-10.31$, $p<.001$) and near ($t(15)=31.99$, $p<.001$) pairings differed significantly from the intermediate rating of 4, indicating that although visual similarity ratings varied across pairing, the similarity between items was not high, even in near condition.

We asked parents to estimate whether their child understood, or understood and produced each of the sixteen stimuli used in our experiment. The results showed that the sixteen stimuli were understood by 80% of the children and produced by 61%. The images were colored photographs, with a mean size of 14 x 8 cm, viewed from a distance of 60 cm. The paired images were displayed horizontally, separated by about 10 cm on a white background using a GeForce 7300 GT card and a CRT display (Sony GDM F520) at 1024x728 pixels.

Table I. Image pairs used in each experimental condition. Cosines of semantic feature similarities (CS) between the concepts taken from McRae et al. (2005) are shown for each image pair.

Semantic Categories	Near			Distant			Unrelated		
	Target	Distractor	CS	Target	Distractor	CS	Target	Distractor	CS
Animals	fox	deer	0.551	fox	sheep	0.329	fox	bowl	0.000
	cow	sheep	0.579	cow	deer	0.332	cow	fork	0.000
Household	spoon	fork	0.546	spoon	bowl	0.292	spoon	deer	0.000
	plate	bowl	0.534	plate	fork	0.094	plate	sheep	0.041
Food	apple	lemon	0.492	apple	beans	0.197	apple	coat	0.000
	cucumber	beans	0.479	cucumber	lemon	0.140	cucumber	scarf	0.086
Clothes	shirt	coat	0.539	shirt	scarf	0.188	shirt	beans	0.000
	gloves	scarf	0.443	gloves	coat	0.318	gloves	lemon	0.000

Auditory stimuli

Spoken target words were eight, one- or two-syllable, basic level French nouns (fox, cow, spoon, plate, apple, cucumber, shirt, gloves). The words were recorded by a female native speaker of French, who was asked to pronounce the words in a neutral voice. The words were recorded at 22,05 KHz sampling rate and edited with Adobe Audition (CS 5.5). The mean duration of the target words was 643 milliseconds (range: 420 ms to 815 ms; SD=132 ms). The words were delivered from two loudspeakers that were located on each side of the computer screen, at a 30° angle to the child’s position on the caregiver’s laps.

Apparatus

Eye movements were sampled monoculary at 500 Hz using the EyeLink 1000 Remote eye trackers system (SR Research, Ontario, Canada) with on-line detection of fixations and a spatial accuracy < 0.5°. A small target sticker was placed on the participants' forehead. The sticker allowed tracking of head position even when the pupil image was lost (i.e., during blinks or sudden movements). A 5-point calibration (using a bouncing ball) and validation procedure was performed before the first trial of each block. Before each trial, a drift correction was performed. The first fixation in each trial was defined as the first fixation that began after the onset of the image.

Procedure

Children were seated on their parents' lap in a dimly lit room. Parents were asked simply to close their eyes (as in Arias-Trejo & Plunkett, 2010), remain silent and not to communicate in any way with their child during the experiment. The presence of two experimenters during each experimental session insured that this procedure is controlled across all participants. Once the child fixated a point located at the middle of the screen, it disappeared, and a trial started. The stimulus display (a pair of a target and a competitor image) was presented for 5.5 seconds, including a pre-naming (3 seconds) and a post-naming (2.5 seconds) phase. After 3 seconds of the display onset, an isolated spoken word was delivered through the loudspeakers. In order to start the next trial, a grey screen appeared again with a centered white point that the child had to fixate. The children viewed 24 trials that were divided in three blocks, eight trials in each block. Breaks were taken between blocks when needed. The presentation order of the trials, as well as the side of the target image - left or right - was randomized. The whole experiment lasted approximately 10 minutes.

Data and Statistical analysis

The proportion of target looking (PTL) was calculated by dividing the amount of time spent looking at the target (T) by the amount of time spent looking at both images, the target and the competitor (T+C) separately in the pre- and post-naming phases. Only the trials during which a child looked at both images in the pre-naming phase were included in the analyses. The total number of trials for the statistical analyses was 630 (214 in near, 214 in distant, and 202 in unrelated condition). The mean number of trials in the three conditions for each child was 21 (7 near, 7 distant and 7 unrelated). The time window of analysis started at 363 ms after the target word onset and ended at 2000 ms. The ≈360 ms starting time is the standard in the field and it has been suggested that earlier fixations cannot plausibly be in response to the spoken target word and that after ≈2000 ms, the re-fixations are random and are not related to the word processing (e.g., Swignley et al., 1999; Swingley & Aslin, 2000, 2002; Bergelson & Swingley, 2012).

Two-way repeated analysis of variance (ANOVA) including the naming phase (pre- and post-naming) and condition (near, distant, unrelated) within-subject factors was performed. We also investigated whether the vocabulary size interacts with the target looking times by including the vocabulary group (normal-high versus normal-low producers) as a between-subject factor. A paired sample Bonferroni *t*-test was used for post-hoc comparisons.

To explore the proportion of target looking across time, the proportion of trials on which children were looking at the target image at each 33-ms interval was calculated. For the statistical comparison we used weighted means for randomization test analyses to determine the time periods where two conditions differed from one another. These statistics were inspired from previous studies using time course analysis (for more details, see Maris & Oostenveld, 2007; Von Holzen & Mani, 2012) and growth curves analysis (Mirman, Dixon & Magnuson, 2008). In behavioural studies, randomization tests, however, were shown to be more powerful than traditional parametric statistics because the data are often not normally distributed and because of the frequent repeated measures of the same individual (e.g., Adams & Antony, 1996; for review, see Manly, 2006).

The response latency was calculated by measuring the time when the child shifted correctly from the competitor to the target image from the spoken word onset. Only the trials were the infants were looking at the competitor at the word onset were used for this analysis.

Results

Accuracy

Although the main effects of *naming phase* ($F(1,29)=4.13$, $p=0.051$) and *condition* ($F(2,58)= 3.06$; $p=0.061$) on the proportion of target looking times were not significant, the interaction between both factors was significant ($F(2,58)=9.38$, $p<.05$). The results showed that participants looked significantly and with greater proportion of time at the target image in the post-naming (64%) than in the pre-naming (53%) phase in the unrelated condition ($t(29)=4.39$, $p<.001$), but not in the near and distant conditions (both *ps*>.05). The proportions of target looking times were, however, significantly above chance both in the distant ($t(29)=3.16$; $p<.05$) and the unrelated ($t(29)= 5.02$; $p<.01$), but not in the near ($t(29)= 0.19$; $p=0.85$) condition. A paired sample *t*-test yielded a significant difference between near and distant ($t(29)=2.59$; $p<.05$) and between near and unrelated conditions ($t(29)= 3.54$; $p<.05$), but the difference between the distant and unrelated conditions did not reach significance (*t*(29)=1.54; *p*=0.13) (**Fig. 1**).

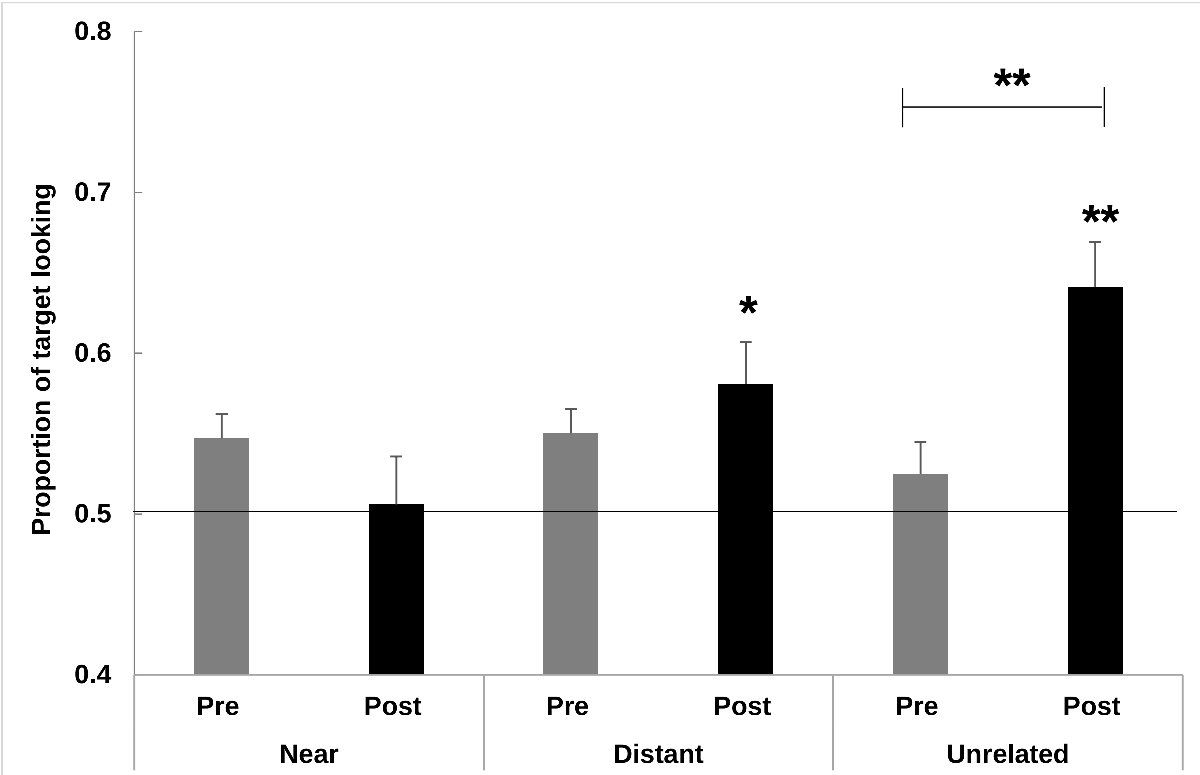


Figure 1. Mean proportions of target looking during pre- and post-naming in the near, distant, and unrelated conditions. Asterisks indicate significant differences between conditions and whether target looking was above chance. The horizontal axis above the unrelated condition indicates significant difference between both naming phases. The vertical lines illustrate the standard error of mean (S.E.M.). [*$p<.05$; **$p<.01$].

Time course analysis

Visual inspection of the proportion of trials in which the target was fixated across time showed that the three conditions started to deviate from one another around the first second from the spoken word onset, with an earlier transient peak of target looking in the near compared to the distant and unrelated conditions (**Fig. 2**). The results revealed that near condition deviated significantly from the unrelated condition between 1023 ms to 2013 ms ($p<.05$). The distant and the unrelated conditions deviated from one another at 1089 ms to 1551 ms ($p<.05$) whereas the deviation between near and distant occurred later between 1452 ms to 1848 ms ($p<.05$).

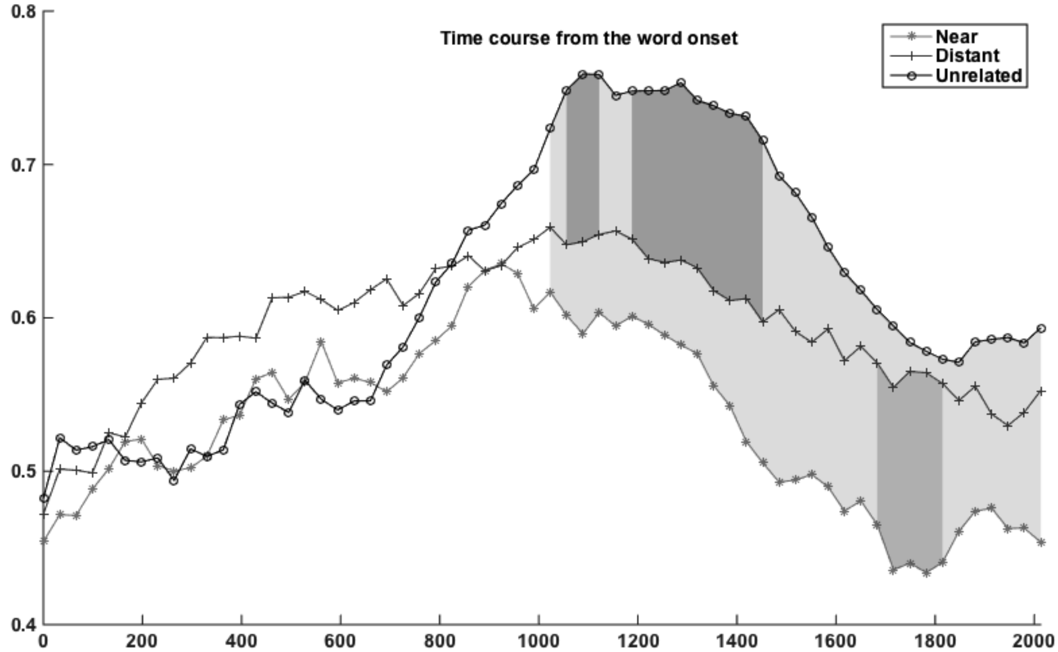


Figure 2. Time course of mean proportions of trials in which children were looking at the target image in near, distant and unrelated conditions. Significant differences between conditions are highlighted with grey shaded boxes. Significant differences between near versus unrelated condition were found during the whole time window (illustrated in light grey), between distant and unrelated conditions from 1089 ms to 1551 ms (dark grey) and between near and distant from 1452 ms to 1848 ms (dark grey).

Response latency

The results showed a significant main effect of *condition* ($F(2,54)= 3.79$; $p<.05$). The response latencies were shorter in the unrelated (1114 ms) than in the distant (1384 ms) and near (1250 ms) conditions (**Fig. 3**). The significant differences were found between near and unrelated ($t(28)= 2.31$; $p<.05$) and between distant and unrelated ($t(28)= 2.24$; $p<.05$) conditions.

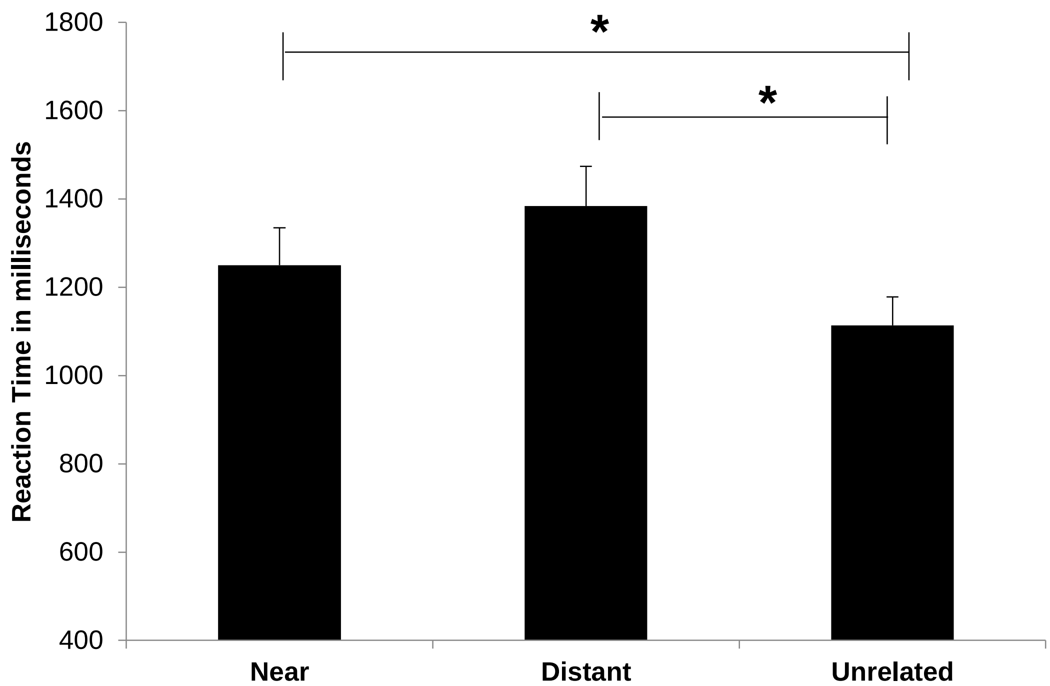


Figure 3. Response latencies in the near, distant and unrelated conditions. Asterisks indicate significant differences between conditions (*$p<.05$).

Vocabulary size effect

In the following analyses, we explored whether productive vocabulary skills interacted with the target looking times of twenty-three participants (77%) for whom the CDI was completed and returned. The median split (287 words) was used to divide the participants into two subgroups with normal to low and normal to high vocabulary sizes. The mean number of words produced was 397 (SD= 75; range: 287 to 502) in the group of normal-high producers (n=12) and 197 (SD= 70; range: 87 to 278) in the group of normal-low producers (n=11). The results showed that the interaction between vocabulary group, condition and naming phase was marginal ($F(2,42)= 2.45$; $p=0.095$). It was still worthwhile to have analyzed the differences between both vocabulary groups. In the normal-low producers, a difference between pre- and post-naming was found only in the unrelated condition ($t(10)= 3.74$; $p<.01$) and proportions of target looking time at the post-naming were above chance only in this condition ($t(10)= 5.84$; $p<.001$). Significant differences were found between near and unrelated ($t(10)= 2.30$; $p<.05$) and between distant and unrelated ($t(10)= 2.68$; $p<.05$) conditions, but not between near and unrelated conditions ($p>.05$; **Fig. 4A**). In the normal-high producers, differences between both naming phases were significant in the unrelated ($t(11)= 4.01$; $p<.01$) and close to significance in the distant ($t(11)= 2.01$; $p=0.069$) conditions. Proportions of target looking times were above chance in the distant ($t(11)= 3.72$; $p<.01$) and unrelated ($t(11)= 2.59$; $p<.05$) conditions. A significant difference was found between the near and distant ($t(11)= 2.57$; $p<.05$) conditions (**Fig. 4B**) but not between near and unrelated or distant and unrelated conditions (all *p*'s>.05).

By comparing both vocabulary groups in each condition and in each naming phase, paired-sample *t*-tests yielded no significant differences (all *p*'s>.05), except for the distant competitor condition that was marginal ($t(10)= 1.86$; $p= 0.092$), indicating that normal-high producers looked more at the target image in the post-naming phase (64%) compared to the normal-low producers (53%).

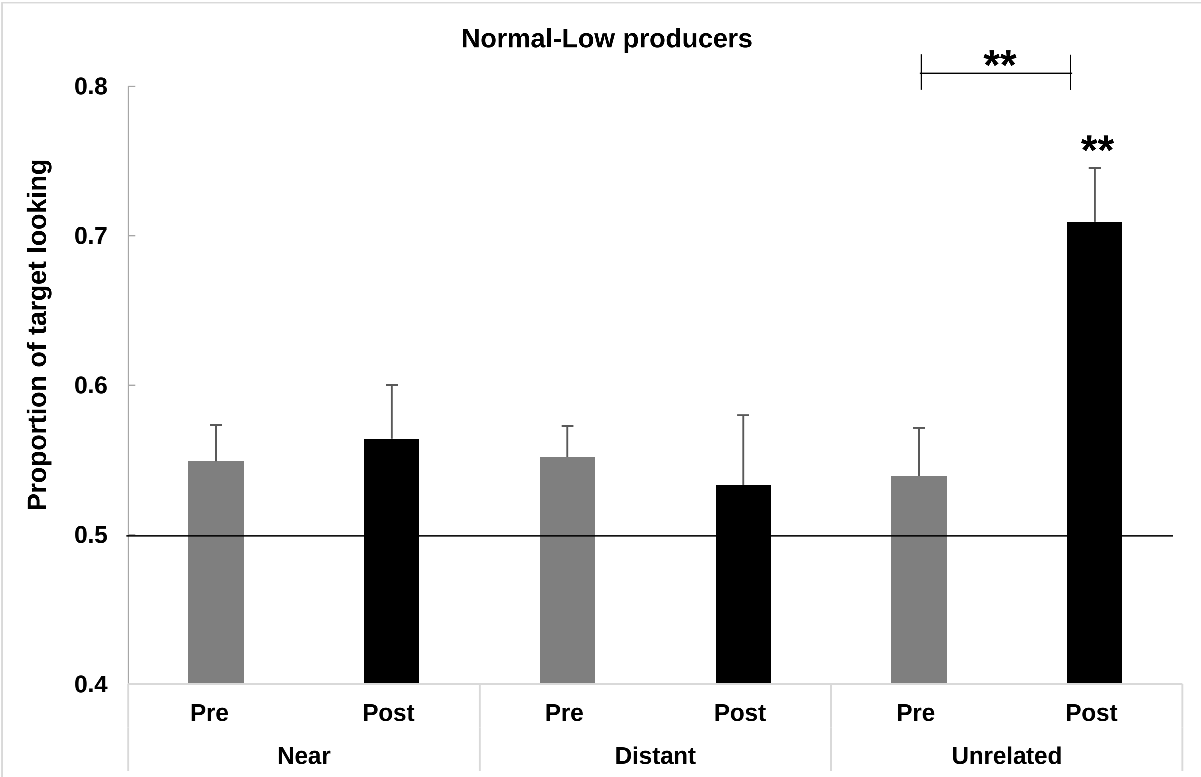


Figure 4A. Mean proportions of target looking in the near, distant, and unrelated conditions in the pre- and post-naming phase for the normal-low producers. The horizontal axis above the unrelated condition indicates significant difference between both naming phases. Asterisks indicate whether target looking was above chance. The vertical lines illustrate the standard error of mean (S.E.M.). [*p<.05; **p<.01]. In the normal-low producers group, significant differences were between near and unrelated and between distant and unrelated conditions (all p's<.05).

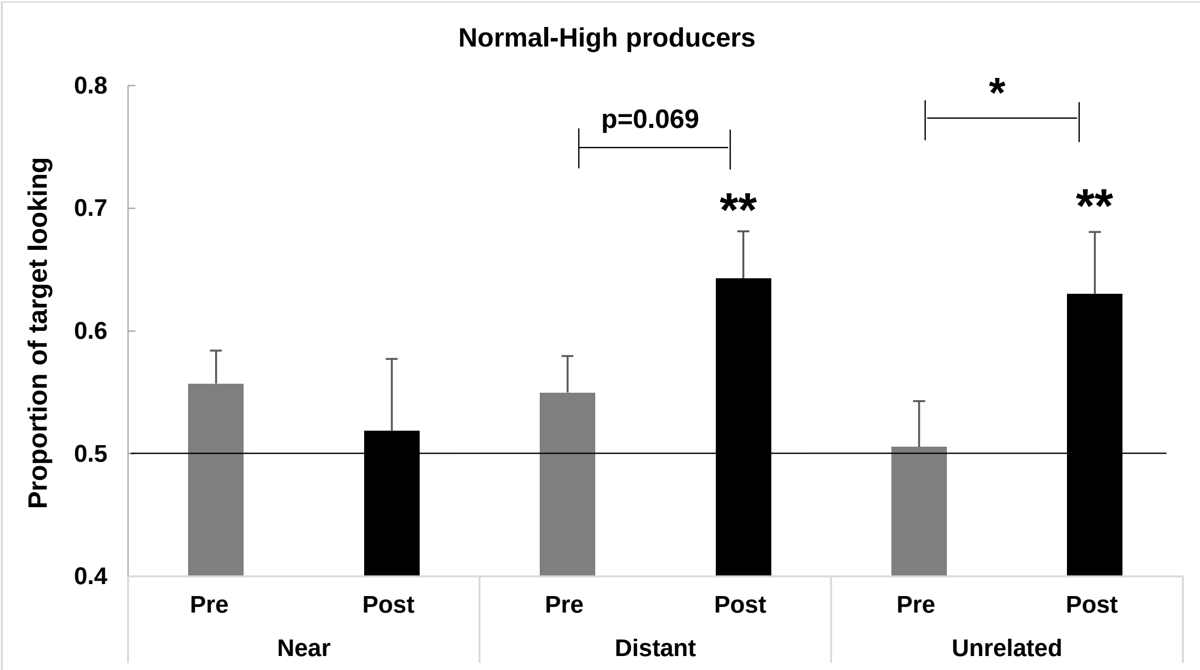


Figure 4B. Mean proportions of target looking in the near, distant, and unrelated conditions in the pre- and post-naming phase for the normal-high producers. The horizontal axis above the unrelated condition indicates significant difference between both naming phases. Asterisks indicate whether target looking was above chance. The vertical lines illustrate the standard error of mean (S.E.M.). [*p<.05; **p<.01]. In the normal-high producers, significant difference was between near and distant condition (all p's<.05).

Discussion

The current study investigated whether the presence of a similar semantic competitor in a LWL task affects word recognition at 24-months of age. The results showed that the proportion of looking times at the named target in the post-naming phase was higher in the unrelated compared to the distant condition. In the near competitor condition, proportions of looking times were equally distributed among the target and competitor images. The reaction times of shifting correctly from the distracter to the target image at the spoken word onset were faster in the unrelated compared to the two other conditions indicating that the speed of word recognition was increased when two items were drawn from different taxonomic categories. In line with previous adults' findings (Cree et al., 1999; Huetting & Altmann, 2005; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Meyer & Damian, 2007; Mirman & Magnuson, 2008, 2009), our results indicate that the likelihood of fixating the competitor is related to its degree of semantic similarity shared with the target.

The expressive vocabulary skills were found to contribute to the target looking times. In normal-low producers, simultaneous presentation of near and distant competitors disrupted word recognition whereas in the normal-high producers, interference occurred only in the near competitor condition. These results suggest that advanced vocabulary development contributes to semantic similarity effects in word recognition task. It has already been demonstrated that vocabulary skills are correlated with accuracy and speed of speech processing, indicating that during the second year, increased experience with words and their production contributes to efficiency in word recognition and understanding (e.g., Fernald et al., 2001; Fernald, 2002; Zangl, Klarman, Thal, Fernald, & Bates, 2005). Furthermore, higher productive vocabulary skills were suggested to induce better lexical representations (e.g., Fernald et al., 2006). In our study, the normal-low producers looked equally the distracter and the target images in both near and distant conditions, demonstrating that even low perceptual similarity disrupts word recognition. On the other hand, normal-high producers were disrupted only by the presence near competitor condition. In line with previous findings, these results suggest that features overlap is a determinant factor for structuring the lexical-semantic system (e.g., Clarck, 1973; Arias-Trejo & Plunkett, 2010) and that enhanced vocabulary contributes to the establishment of similarity distances between lexical items, allowing young children to develop more sophisticated semantic organization.

The proportion of target looking differed across time. The differences in proportion of looking times between both near and unrelated (from 1023 to 2000 ms) and between distant and unrelated (from 1089 to 1551 ms) conditions were observed earlier than between near and distant (from 1452 to 1848 ms) conditions. These findings reveal that the temporal dynamics of semantic activation reflects a graded similarity distance between the items. Our time courses are similar to those previously reported in young children (Arias-Trejo & Plunkett, 2010), but differ from those found in adults (e.g., Huettig & Altmann, 2005; Mirman & Magnuson, 2009). Adults look systematically more at the target than at the near or distant competitor, but they show transient, increased looking to near or categorical competitors at the beginning of the trial. Our participants looked at the target images less in the near than in the unrelated condition during the whole trial, indicating that semantic competitor effect was longer lasting than in adults. In future studies, it remains to be investigated whether the time course of activation would be more similar to adults when more items are presented simultaneously on the visual display.

Our findings indicate that semantic similarity between the target and competitor images, categorical and other (e.g., perceptual, functional) influences the word recognition. Nevertheless, other alternatives might explain the present results. First, visual similarity between items has been shown to induce competition during word recognition both in adults (e.g., Huettig & Altmann, 2004; Dahan & Tanenhaus, 2005; Huettig & Altmann, 2005; Huettig & McQueen, 2007) and in children (Arias-Trejo & Plunkett, 2010). Yet, visual similarity is difficult to estimate as similarity ratings are influenced by categorical similarity (Goldstone, Lippa, & Shiffrin, 2001). That is, in the near competitor condition, equal looking time to both images might be due to high perceptual similarity. In the current study, adult participants rated the similarity between image pairs, separately for shape, colour, and surface texture. The results revealed that even though in the near condition, paired images were rated as visually similar, more than distant and unrelated images, the similarity scores were not very high. Moreover, Mirman & Magnuson (2009) conducted growth curve analyses for fixation data, and found that when semantic similarity was added to the model that already included visual similarity, the model improved significantly, suggesting that fixations to semantic competitors were driven by semantic rather than by visual similarities. Although in young children visual similarity has been shown to contribute to target looking times when both images are from the same semantic category (Arias-Trejo & Plunkett, 2010), it has been recently suggested that at 24-month-olds, word processing is more affected by semantic features rather than by perceptual similarities (Mani, Johnson, McQueen, & Huettig, 2013). In that study, children heard the prime '*banana*', paired with by either a perceptually similar (e.g., yellow cup) or categorically similar (e.g., cookie) targets. The results showed that children were faster at shifting their gaze to the semantically related compared to the colour-matched target, indicating that semantic knowledge is a more salient aspect than visual similarity for word meanings. Second, we do not rule out the possibility that participants might be still overextending highly similar items. Still, if it were for overextension, looking to the target in the post-naming phase would have not been above chance even in the distant competitor condition. This may be the case of normal-low producers, since both near and distant competitor interfered with word recognition, assuming that improved vocabulary skills decrease the overextensions. However, due to the small sample size in each of the vocabulary groups, this hypothesis cannot be confirmed. Further investigations are needed in order to clarify the interaction between semantic similarity distance, vocabulary size, and overextension.

To conclude, our results reveal that in the developing lexical-semantic system, words are organized according their categorical relationships and to their shared features. It should be also kept in mind that taxonomic relationships are often thought to derive from overlap in semantic features, such as, perceptual, conceptual or functional feature (Thompson-Schill et al., 1998) and therefore semantic similarities are inevitable. Our findings suggest a gradient semantic activation in word recognition task based on semantic similarity distances. The simultaneous presence of a semantic competitor affected the target word recognition and this effect was more prominent when two concepts shared many semantic features. The time course analysis revealed that conditions started to deviate one from another one second after the spoken word offset and that even these temporal differences depended on the similarity distances between items.

Acknowledgement

We thank all families for participating and contributing to this research. We would also like to acknowledge Lionel Granjon for his help in the time courses analyses. This study was funded by the Sorbonne Paris Cité Grant.

References

Adams, D.C., & Antony, C.D. (1996). Using randomization techniques to analyse behavioural data. *Animal Behaviour*, 51, 733-738.

Arias-Trejo, N., & Plunkett. K. (2009). Lexical–semantic priming effects during infancy. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364* (1536), 3633–3647.

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* (1-2), 63-80.

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.

Bergelson, E., & Swingley, D. (2013). Young toddlers' word comprehension is flexible and efficient. *Plus one, 8* (8), 1-9.

Bloom, L. (1973). One word at a time: the use of the single-word utterances before syntax. The Hague: Mouton.

Bloom, P., & Markson, L. (1998). Capacities underlying word learning. *Trends in Cognitive Sciences, 2* (2), 67-73.

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

Dahan, D., & Tanenhaus, M.K. (2005). Looking at the rope when looking for the snake: conceptually mediated eye movements during spoken-word recognition. *Psychonomic Bulletin & Review, 12* (3), 453-459.

Dale, P.S., & Fenson, L. (1996). Lexical development norms for young children. *Behavioral Research Methods, Instruments, & Computers, 28,* 125-127.

Delle Luche, C., Durrant, S., Floccia, C., & Plunkett, K. (2014). Implicit meaning in 18-month-old toddlers. *Developmental Science,* 1-8.

Fenson, L., Dale, P.S., Reznick, S., Thal, D., Bates, E., & Hartung, J. (1993). MacArthur communicative development inventories: user's guide and technical manual. San Diego, CA: Singular publishing group.

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* (1), 98-116.

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* (3), 228-231.

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

Fernald, A., Zangl, R., Portillo, A.L., & Marchman, V.A. (2008). Looking while listening: using eye movements to monitor spoken language comprehension by infants and young children. In: Sekerina, I.A., Fernandez, E.M., & Clahsen, H. (2008). *Developmental Psycholinguistics: On-line methods in children's language processing,* John Benjamins: Amsterdam, 97-135.

Ganger, J., & Brent, M.R. (2004). Reexamining the vocabulary spurt. *Developmental Psychology, 40* (4), 621-632.

Goldstone, R. L., Lippa, Y., & Shiffrin, R. M. (2001). Altering object representations through category learning. *Cognition, 78*(1), 27-43.

Golinkiff, R.M., Hirsh-Pasek, K., Cauley, K.M., & Gordon, L. (1987). The eyes have it: lexical and syntactic comprehension in a new paradigm. *Journal of Child Language, 14*, 23-45.

Huettig, F., & Altmann, G.T.M. (2004). The online processing of ambiguous and unambiguous words in context: evidence from head-mounted eye-tracking. In M. Carreiras, & C. Clifton (Eds.), *The online study of sentence comprehension: eye-tracking, ERP and beyond* (pp. 187-207). New-York, NY: Psychology Press, 187-207.

Huettig, F., & Altmann, G.T.M. (2005). Word meaning and the control of eye-fixation: semantic competitor effects and the visual world paradigm. *Cognition, 96* (1), 23-32.

Huettig, F., & Altmann, G.T.M. (2007). Visual-shape competition during language-mediated attendtion is based on lexical input and not modulated by contextual appropriateness. *Visual Cognition, 15* (8), 985-1018.

Huettig, F., Rommers, J., Meyer, A.S. (2011). Using the visual world paradigm to study language processing: a review and critical evaluation. *Acta Psychologia, 137* (2), 151-171.

Magnuson, J. S., Dixon, J.A., Tanenhaus, M.K., & Aslin, R.N. (2007). The dynamics of lexical competition during spoken word recognition. *Cognitive Science, 31* (1), 133-156.

Mani, N., & Johnson, E. (2013). How yellow is your banana? Toddlers' language-mediated visual search in referent-present tasks. *Developmental Psychology, 49* (6), 1036-1044.

Manly, B.F.J. (2006). Randomization, Bootstrap and Monte Carlo methods in biology. In: *Texts in Statistical Science*, 3rd edition. Chapman & Hall/CRC.

Maris, E., & Oostenveld. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*, 177-190.

McRae, K., Cree, G. S., Seidenberg, M. S. & Mcnorgan, C. (2005). Semantic feature production norms for a large set of living and nonliving things. *Behavior Research Methods, 37* (4), 547–559.

Mills, D.L., Plunkett, K., Prat, C., & Schafer, G. (2005). Watching the infant brain learn words: effects of vocabulary size and experience. *Cognitive Development, 20,* 19-31.

Mirman, D., & Magnuson, J. S. (2008). Attractor dynamics and semantic neighborhood density: processing is slowed by near neighbors and speeded by distant neighbors. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 34*, 65-79.

Mirman, D., & Magnuson, J. S. (2009). Dynamics of activation of semantically similar concepts during spoken words recognition. *Memory & Cognition, 37* (7), 1026-1039.

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

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.

Reznick, J.S. (1990). Visual preference as a test of infant word comprehension. *Applied Psycholinguistics, 11*, 145-166.

Styles, S. J., & Plunkett, K. (2009). How do infants build a semantic system? Language and *Cognition, 1* (1), 1–24.

Swingley, D., & Aslin, R.N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition, 76* (2), 147–166.

Swingley, D., & Aslin, R.N. (2002). Lexical neighborhood and the word-form representations of 14-month-olds. *Psychological Science, 13* (5), 480-484.

Swingley, D., & Fernald, A. (2002). Recognition of words referring to present and absent objects by 24-month-olds. *Journal of Memory and Language, 46*, 39-56.

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

Thompson-Schill, S.L., Kurtz, K.J., & Gabrieli, J.D.E. (1998). Effects of semantic and associative relatedness on automatic priming. *Journal of Memory and Language, 38* (4), 440-458.

Torkildsen, J. von Koss, 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.

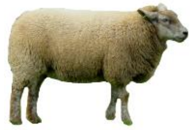
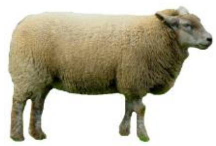
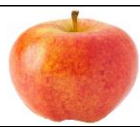
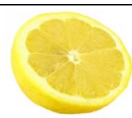
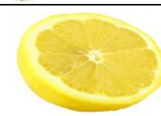
Von Holzen, K., & Mani, N. (2012). Language nonselective lexical access in bilingual toddlers. *Journal of Experimental Child Psychology, 113*, 569-586.

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), advanced online publication, doi: 10/1111/infa.12026.

Yee, E., & Sedivy, J. C. (2006). Eye movements to pictures reveal transient semantic activation during spoken word recognition. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 32*, 1-14.

Yee, E., Overton, E., & Thompson-Schill, S.L. (2009). Looking for meaning: eye-movements are sensitive to overlapping semantic features, not association. *Psychonomic Bulletin & Review, 16* (5), 869-874.

Appendix I.

Named Target Image	Near competitor	Distant competitor	Unrelated competitor
			
			
			
			
			
			
			
			

[Study IV: In preparation]

Two languages, one mind: Within language priming in French-Spanish bilingual toddlers

Louah Sirri [1] & Pia Rämä [1, 2]

[1]Université Paris Descartes, Sorbonne Paris Cité, Paris, France

[2] CNRS, Laboratoire Psychologie de la Perception (UMR 8242), Paris, France

Correspondance:

Louah Sirri

Laboratoire Psychologie de la Perception (CNRS UMR 8242)

Université Paris Descartes

45, rue des Saints-Pères, 75006 Paris, France

Email: louah.sirri@gmail.com

Tel : +33 (0)1 42 86 40 65

Fax: +33 (0)1 42 86 33 22

Abstract

Recent event-related brain potential (ERP) studies have shown that lexical items are organized according to their semantic relatedness at the age of 24 months or even earlier, at the age of 18 months in monolingual children. Semantic relatedness effect in these auditory priming tasks was reflected by a negative waveform, N400 response, which was more pronounced for unrelated than for related spoken target words (N400 effect). Yet, even less is known about the lexical-semantic processing in bilingual toddlers and whether they are sensitive to semantic relatedness between words in both of their languages. To answer these questions, the present study investigated the occurrence of language related ERPs (N2 and N400) in response to spoken words in within-language priming task. Participants were seventeen French-Spanish bilingual children. Words were either semantically related (e.g., horse-bear *versus* caballo-oso) or unrelated (e.g., chair-bear *versus* silla-oso) spoken words in each of the languages. The preliminary results revealed more negative amplitudes for unrelated than for related target of the languages. However, the lateralization of the frontally distributed N2 and the posteriorly distributed N400 varied across the dominant and the non-dominant language. For French words, the N2 effect was more pronounced over the left than the right hemisphere whereas for Spanish, more pronounced N2 effect was found over the right hemisphere. The N400 effect for French words occurred over both hemispheres while for Spanish the effect was right lateralized. These findings suggest that words are taxonomically organized in both bilinguals' languages, but distinct neural resources might underpin semantic processes.

Introduction

There is evidence that ERPs associated with lexical-semantic processing in bilingual adults differ from those of monolinguals and also vary according to the dominant (L1) and the non-dominant (L2) languages. Several studies conducted both with monolingual and bilingual adults compared the N400 semantic priming effect in each of the bilinguals' two languages and to monolinguals (e.g., Ardal, Donald, Meuter, Muldrew, & Luce, 1990; Hahne & Friederici, 2001; Proverbio, Cok, & Zani, 2002; Moreno & Kutas, 2005). It has been shown that the N400 is delayed in the bilinguals' L2 compared to their L1 (Ardal et al., 1990; Hahne & Friederici, 2001; Moreno

& Kutas, 2005). In some studies, not only the N400 peaked later in L2, but its amplitudes in L2 were also reduced as opposed to L1 (Ardal et al., 1990; Proverbio et al., 2002). The N400 was shown to peak later even in the bilinguals' L1 when compared to monolinguals (Ardal et al., 1990; Weber-Fox & Neville, 1996; Hahne, 2001). Moreover, in some studies, the distribution of the N400 varied according to the processed language (L1 *versus* L2) and between the linguistic groups (monolinguals *versus* bilinguals). The N400 was more pronounced over the right hemisphere for L2 than for L1 (Hahne & Friederici, 2001). For both bilingual's languages, the N400 was observed over the left hemisphere in bilinguals and over the right hemisphere in monolinguals (Ardal et al., 1990; Proverbio et al., 2002). It has been suggested that slower latencies of the N400 in bilinguals compared to monolinguals reflect slower semantic processing and less automatized lexical access in bilinguals. As for the differences in distribution, it has been suggested that distinct neural mechanisms underlie lexical-semantic processing in the dominant and non-dominant languages (for a review, see Moreno, Rodriguez-Fornells, & Laine, 2008).

To date, there are only a few studies that investigated semantic processing in bilingual children. Conboy and Mills (2006) showed that in 19- to 22-month-old children, language-related ERPs occurred earlier for the dominant as opposed to the non-dominant language. The N200-400 component was more pronounced over the right than the left hemisphere for the dominant language. For the non-dominant language, no such asymmetry was obtained. The right-lateralization of the N400-600 was found to correlate with the child's vocabulary skills in the dominant language. These findings suggest that distinct neural generators might be engaged during lexical-semantic processing of two languages (Conboy & Mills, 2006). Further, 11-month-old bilingual infants displayed N2 and N4 in response to familiar words, in both the dominant and non-dominant languages (Vihman, Thierry, Keren-Portnoy, & Martin, 2007). The N2 peaked almost at the same time in bilingual and monolingual infants. When both bilinguals' languages were compared, the N2 and N4 were shown to peak later in the non-dominant as opposed to the dominant language. The authors suggested that these latency differences might be due to faster neural processing in the dominant language (Vihman et al., 2007). Using behavioral within- and cross-language priming tasks, it was recently shown that priming effects occur only for the dominant language or when the prime word is in L1 and the target word in L2, suggesting that semantic processing might differ across languages (Singh, 2014).

In the present study, we investigated whether N2 and N400 components in response to lexical-semantic processing occur for both languages of 2-4 years old French-Spanish bilingual toddlers and whether these components are similarly distributed across the scalp for L1 and L2. Children were exposed to an auditory within-language priming task, while the ERPs were recorded. Spoken word pairs in both languages, French or Spanish, were either taxonomically related (e.g., dog–donkey) or unrelated (e.g., tummy–donkey). The underlying hypotheses were as follows: First, the occurrence of the N2 and N400 components for both languages would indicate that auditory lexical-semantic processing is identical for the dominant and non-dominant languages. Second, differences in lateralization or distribution of the priming effects would indicate that distinct neural mechanisms underlie lexical-semantic processing in the dominant and non-dominant languages.

Methods

Participants

Seventeen 2 to 4 years old (mean age: 36 months and 4 days; range: 23 months, 21 days to 54 months, 22 days) children participated to the study. The children were recruited from a database of parents who voluntarily participated in previous studies in child development in our laboratory and came from the Paris area. All children were born full-term and presented no hearing deficits or language impairment. Parents were informed about the aim of the study and its procedure before participating and gave informed consent. Children were raised in a family where the mother spoke Spanish and the father French (n = 13), or father spoke Spanish and the mother French (n = 3). In one family, the mother spoke Spanish and the Father Italian and the child was learning French at a day care. Parents filled the language background questionnaire and estimated the amount of their children's total exposure to each language. According to the results, we defined French as the children's dominant language (60% of total exposure) and Spanish as the non-dominant language (39% of total exposure), the latter was influenced by the general estimation of one participant who was trilingual (60% French – 20% Spanish – and 20% Italian). Five additional children were recruited but their data were excluded from the analyses because of experimental equipment failure (n = 1), noisy EEG recordings (n = 1), or insufficient number of trials in one of the experimental conditions (n = 3). Parents were given the list of words used in the experiment and were asked to evaluate how many words their children understood or understood and produced. The questionnaire was returned for sixteen of the seventeen children in our final sample, including one participant for whom only the Spanish part was filled. Parents' estimation revealed that children understood 94% (136 words; range 88-144) and produced 78% (112 words; range 14-144) of the French words used in the experiment, and understood 82% (118 words; range: 47-144) and produced 53% (77 words; range: 1-139) of the words used in Spanish. The study was conducted in conformity with the declaration of Helsinki and approved by the Ethics Committee of the University of Paris Descartes.

Stimuli

The stimuli were French basic level nouns (144 words) and their Spanish translation (144 words) from different semantic categories (animals, clothes, body parts, food, furniture, transportation, household items, persons, nature and places to go). The words were presented in four different female voices, two in each language, preventing children from associating one voice to a given language. The speakers were two native speakers of French and two native speakers of Spanish, who were asked to pronounced words in a neutral way. The 288 words were arranged into two lists of 72 related and 72 unrelated prime-target word pairs in each language. The two lists were then divided into four experimental blocks, two in French and two in Spanish containing each 36 related and 36 unrelated word pairs. Words were either taxonomically but not associatively related (e.g., chien (dog) – âne (donkey)) or unrelated (e.g., ventre (tummy) – âne (donkey)) in French and their translation equivalents in Spanish. The mean durations of words were 542 ms in French and 520 ms in Spanish. Paired-sample *t*-test revealed that differences between these mean durations were significant ($t(71)= 2.33$; $p<.05$). The recordings were edited with Adobe Audition (CS 5.5) and normalized at 22 kHz sampling rate with Praat (5.3.19).

Procedure

Children were seated by themselves on a chair next to their parents in a dimly lit room at 140 cm from the two loudspeakers. They were allowed to play with toys or draw with crayon placed on a table in front of them and parents were instructed not communicate orally with their children. During the experiment, no visual stimuli were presented. The invariant stimulus onset asynchrony (SOA) was 1000 ms and the intertrial interval (ITI) was 2200 ms. Presentation order of trials was randomized. In both languages, French and Spanish, each prime and target word was repeated twice, once in the related and once in the unrelated condition. Prime and target words in a given trial were always spoken by two different speakers. Each experimental session varied across participants and started either with a French or Spanish block (French-Spanish-French-Spanish, n = 8 and Spanish-French-Spanish-French n = 9). The whole experiment lasted about 17 minutes.

Event-related potential recordings and data analyses

The electroencephalogram (EEG) was continuously recorded from a 128-channel Hydrocel Geodesic Sensor Net, referenced online to the vertex (Cz). The raw signal was amplified with an EGI NetAmps 400 amplifier, filtered (0.1 to 100 Hz bandpass) and digitized at 250 Hz sampling rate. Impedances were kept below a threshold of 100 kΩ. The EEG was filtered offline (0.3-30 Hz) and segmented into 800 ms epochs from word onset that were averaged according to a 200-ms pre-stimulus baseline. Eye blinks and eye movements were detected and removed using the ocular artifact removal (OAR) algorithm (Graton, Coles, & Donchin, 1983). Trials including artifacts exceeding ± 170 μV were rejected. Data from rejected bad channels were replaced using spherical spline interpolation. Segments including more than 40 bad channels were rejected. We averaged segments separately for each subject, target word type (related and unrelated) and language (French and Spanish) and re-referenced those segments to an average reference. The mean number of trials was 26 (SD= 14) for related and 28 (SD= 14) for unrelated targets in French and 25 (SD= 11) for related and 23 (SD= 11) for unrelated targets in Spanish.

Data analyses

The analysis of variance (ANOVA) included as within-subject factors the trial type (related *versus* unrelated target word), language (French *versus* Spanish), area (frontal and posterior), and hemisphere (left *versus* right) factors. The mean amplitudes were calculated separately for each electrode. In each recording area, the mean amplitudes extracted from twelve electrodes were averaged. The midline electrodes were excluded from the statistical analyses, resulting in 48 channels in 4 regions of interest. The 48 channels with their equivalents according to the 10-10 international system of electrodes sites are as follow: 12, 18, 19, 20, 22, 23, 24, 25, 26, 27, 28, 33, in the left frontal, 2, 3, 4, 5, 8, 9, 10, 117, 118, 122, 123, 124 in the right frontal, 52, 57, 58, 59, 60, 61, 64, 65, 66, 67, 70, 71, in the left posterior, and 76, 77, 78, 83, 84, 85, 90, 91, 92, 95, 96, 100, in the right posterior recording sites. A specific time-window of interest, from 200 to 500 ms, that have earlier been associated with two ERP components of interest was chosen for the statistical analyses. This time-window reflects the N2 over the frontal area and the N400 over the posterior area. The statistical analyses were conducted with SPSS (IBM SPP statistics, version 20) and the Greenhouse-Geisser correction was applied for nonsphericity when appropriate.

Results

The visual inspection of ERPs in response to target words showed more negative amplitudes for related than for unrelated target words in both languages over the frontal recording sites. However, the ERPs for L1 and L2 differed in terms of their lateralization. For French target words, negative amplitudes were more prominent over the left hemisphere whereas for Spanish, they were more prominent over the right hemisphere. Inversely, over the posterior recording sites, the amplitudes were more negative for unrelated than for related target words in both languages. For French the negativity was symmetrically distributed whereas for Spanish it was more pronounced over the right hemisphere.

A four-way repeated measures of ANOVA including *2* (trial type) x *2* (language) x *2* (areas) x *2* (hemisphere) was conducted to investigate whether the amplitudes and distribution of N2 and N400 components were modulated according to the language. The results showed that the main effects of trial type ($F(1,16) = 0.02$; $p = 0.89$) and language ($F(1,16) = 0.29$; $p = 0.59$) on the amplitudes of N2 and N400 were not significant. Even so, the trial type interacted significantly with the area ($F(1,16) = 4.52$; $p < .05$) indicating that the negativities in response to spoken words were reversed. Over the frontal recording sites, the N2 was more negative for related compared to unrelated target words whereas over the posterior recording sites the N400 was more negative for unrelated as opposed to related target words. There was also a trend to a significant *trial type x language x area x hemisphere* interaction ($F(1,16) = 3.98$; $p = 0.064$), demonstrating that the amplitudes of N2 and N400 in each language were modulated according to the recording site and hemisphere. Consequently, we conducted separate analysis for each region of interest.

Over the frontal recording sites, the main effect of trial type on the N2 amplitudes was close to significance ($F(1,16) = 4.38$; $p = 0.053$). The amplitudes were more negative for related compared to unrelated target words. Also, there was a significant interaction between trial type, language, and hemisphere factors ($F(1,16) = 5.79$; $p<0.05$). For French target words, the N2 effect (mean amplitudes of unrelated *minus* related) was more pronounced over the left compared to the right hemisphere, whereas in Spanish, the effect was more prominent over the right compared to the left hemisphere (**Fig. 1A and 1B**). However, paired sample *t*-test revealed that these differences were not statistically significant (all *ps*>0.05).

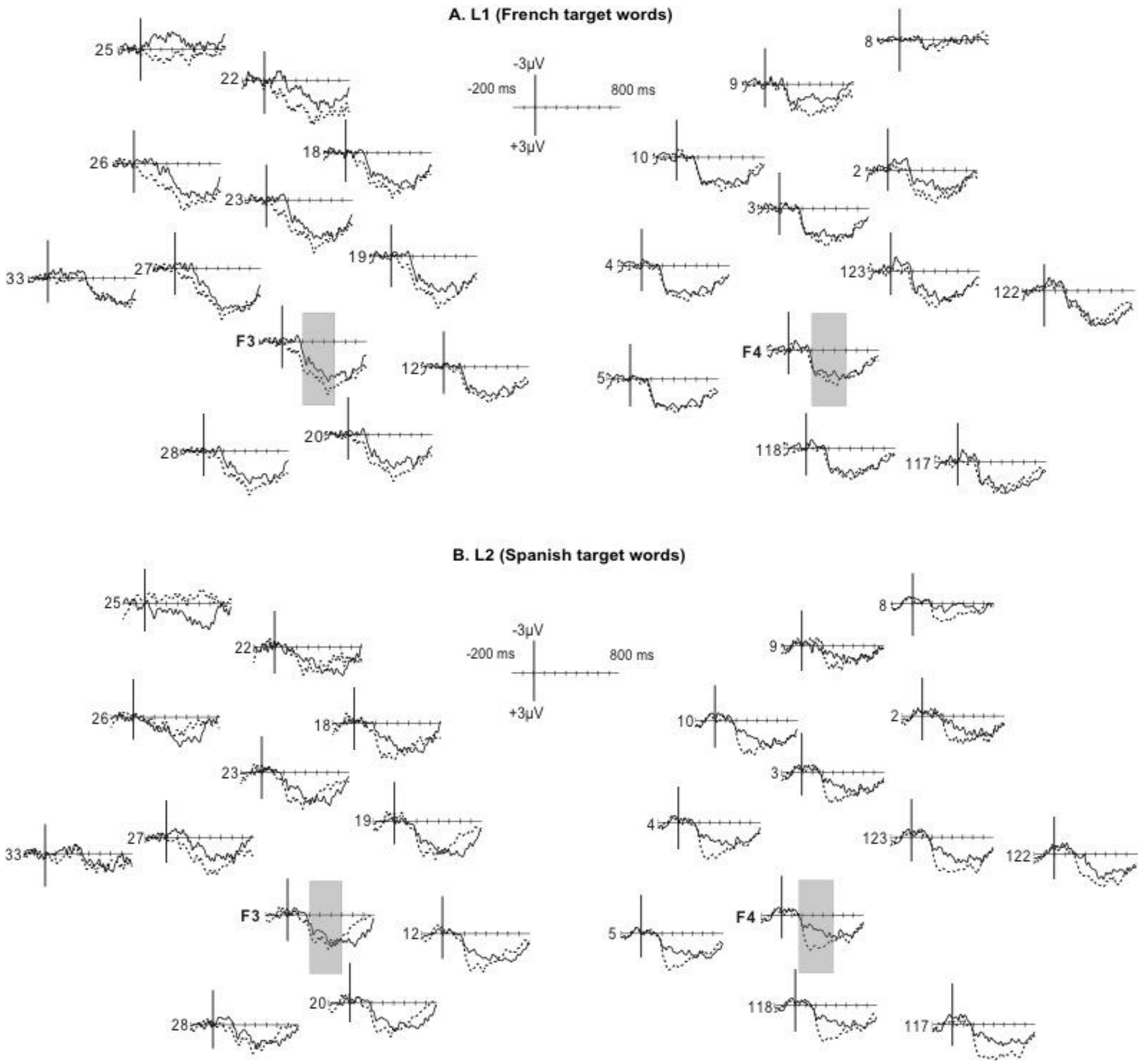


Figure 1. Grand-averaged waveforms for related (solid line) and unrelated (dashed line) target words in French (**A**) and Spanish (**B**) over the frontal recording sites. The vertical lines illustrate the target word onset. The light grey box indicates the occurrence of the N2 component at F3 and F4 electrode positions.

Over the posterior recording sites, the main effect of trial type was close to significance ($F(1,16)= 4.12$; $p=0.059$), with more negative amplitudes for unrelated (-2.67 µV) than for related (-1.44 µV) target words (**Fig. 2A and 2B**). Even though visual inspection of ERPs demonstrate differences in the distribution of the N400 across languages, the interaction between trial type, language, hemisphere was not statistically significant ($F(1,16)= 0.12$; $p = 0.74$).

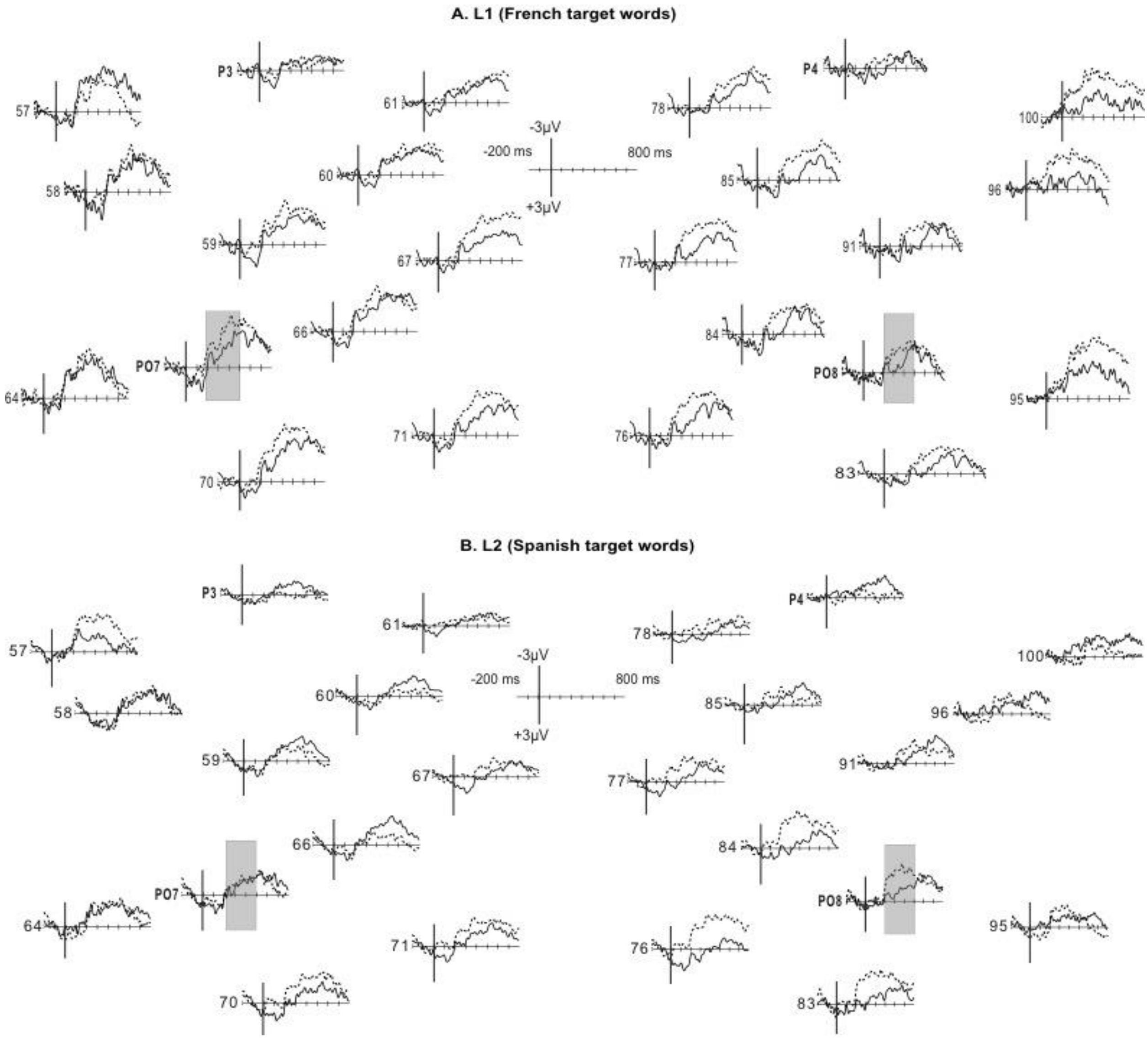


Figure 2. Grand-averaged waveforms for related (solid line) and unrelated (dashed line) target words in French (**A**) and Spanish (**B**) over the posterior recording sites. The vertical lines illustrate the target word onset. The light grey box indicates the occurrence of the N400 component at PO7 and PO8 electrode positions.

Conclusion

The present study revealed that in young bilinguals, words are taxonomically organized in both the dominant and the non-dominant languages as indexed by the occurrence of the N2 and N400 components in response to unrelated target words. However, the distribution of both components varied across the languages, suggesting that when processing semantic relationships between words in the dominant and the non-dominant languages, distinct neural resources might be engaged.

[Study V: In revision]

Different distribution of N400 translation priming effect for dominant and non-dominant languages in bilingual children

Pia Rämä [1, 2] & Louah Sirri [1]

[1]Université Paris Descartes, Sorbonne Paris Cité, Paris, France

[2] CNRS, Laboratoire Psychologie de la Perception (UMR 8242), Paris, France

Correspondance:

Pia Rämä

Laboratoire Psychologie de la Perception (CNRS UMR 8242)

Université Paris Descartes

45, rue des Saints-Pères, 75006 Paris, France

Email: pia.rama@parisdescartes.fr

Tel : +33 (0)1 42 86 40 65

Fax: +33 (0)1 42 86 33 22

Abstract

The present ERP study aimed at determining whether the N400 translation priming effect occurs in 2-4 years old bilinguals. Children were exposed to spoken French-English and English-French prime-target word pairs. The N400-like component was more negative for target words preceded by translated than by unrelated primes, but the scalp distribution depended on the target word language. For forward translation, the effect was found over the left posterior scalp position, whereas for backward translation, the effect was distributed over the frontal scalp positions. The results suggest that neural representations underlying lexical-semantic processing in dominant and non-dominant languages are not identical.

Key words: Cross-language translation priming, language development, bilingualism, and N400

1. Introduction

There is increasing evidence that lexical-semantic language organization starts to develop at the end of the second year of life in monolingual children (e.g., Torkildsen et al., 2006, 2007; Arias-Trejo & Plunkett, 2009; 2013; Styles & Plunkett, 2009; Rämä, Sirri, Serres, 2013; Willits et al., 2013). It has been shown that 24-month-old, but not younger, children look longer the named target in an inter-modal preferential looking (IPL) task when it is preceded by a related than by an unrelated word, indicating that their target looking times are influenced by preceding linguistic information (Arias-Trejo & Plunkett, 2009, 2013; Styles & Plunkett, 2009). This suggests that by the age of 24 months, children are sensitive to semantic relatedness between words. In event-related potential (ERP) studies, the N400 component, shown to be an index of semantic processing (for review, see Kutas & Federmeier, 2011), has been observed in infants as young as 12 months exposed to semantic incongruence tasks (Friedrich & Friederici, 2004, 2005, 2006; Torkildsen et al., 2006). In priming tasks, the N400 semantic priming effect has been found in 18- and 24-months-olds (Torkildsen et al., 2007; Rämä, Sirri, & Serres, 2013). The occurrence of the N400 in developing brain has been correlated, in addition to activation of semantic representations, with brain maturation and established lexical-semantic memory representations (Friedrich & Friederici, 2010). Altogether, both behavioural and neurophysiological findings indicate that by the age of two years, monolingual children have gained a sufficient amount of experience and familiarity with words of their native language to build an interconnected lexical-semantic network.

For bilingual children, however, linguistic experience is divided between their two languages, which results in less experience with words of each language compared with monolingual children, which might, in turn, affect the development of their lexical-semantic system(s). They need to construct in parallel two different phonological-lexical systems and learn two words for each object or concept. Despite of this, bilingual children are suggested to achieve their language milestones in each of their languages at the same age (e.g., Pearson, Fernandez, & Oller, 1993; Oller, Eilers, Urbano, & Cobo-Lewis, 1997; Petitto, Katerelos, Levy, Gauna, Tétreault, & Ferraro, 2001). They distinguish between two languages at young age (Bosch & Sebastián-Gallés, 1997; 2001) and the development of native phonetic representations is not delayed by an exposure to an additional language (Burns, Yoshida, Hill, & Werker, 2007). With sufficient amount of experience with both languages, bilingual infants are shown to be even more sensitive to prosodic properties of language than monolinguals at the age of 10 months (Bijeljac-

Babic, Serres, Höhle, & Nazzi, 2012) and they are also shown to maintain longer sensitivity to language differences while watching silent talking faces than monolinguals (Weikum, Vouloumanos, Navarra, Soto-Faraco, Sebastián-Gallés, & Werker, 2007). However, bilingual children seem to learn similar-sounding words later than monolingual children, at the age of 20 months instead of 17 months (Fennell, Byers-Heinlein, & Werker, 2007). At the age of 17–18 months, bilinguals show also a weaker use of disambiguation that is, associating a novel noun with a novel referent, probably due to acquisition of translation equivalents, which might disturb one-to-one mappings between words and concepts (Byers-Heinlein & Werker, 2009). There is also evidence that bilinguals tend to have a smaller vocabulary in each of their languages even if total vocabulary has reported to be comparable to that of monolinguals (e.g., Bialystok, 2009; Hoff, Core, Place, Rumiche, Senor, & Parra, 2012; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

There are only a few investigations using ERPs to study neural representations of word recognition or word familiarity effect in young bilingual children (e.g., Conboy & Mills, 2006; Vihman, Thierry, Lum, Keren-Portnoy, Martin, 2007; Kuipers & Thierry, 2012, 2013). Vihman and colleagues (2011) explored a word familiarity effect, by comparing ERPs in response to familiar and rare words, in mono- and bilingual 9-12-months-old English-Welsh learning infants. Their results showed that word familiarity effect, as reflected by two negative ERP components, N2 and N4, occurred earlier in age in monolinguals than in bilinguals. In addition, the peak latencies for words in the non-dominant language were delayed as opposed to words in the dominant language (Vihman et al., 2007). Conboy & Mills (2006) studied English-Spanish learning toddlers (19–22 month old) who were also presented with known and unknown words in both of their languages. In their study, the N200-400 familiarity effect was more pronounced for dominant than for non-dominant language. The effects were larger over the right than the left frontal sites for the dominant language whereas such an asymmetry was not observed for the non-dominant language, suggesting that neural representations of words in two languages in bilingual brain are not identical. In a recent study, 2-3 years old monolingual and bilingual toddlers were presented with English words (their dominant language) following by a picture that either matched or not the meaning of the words while ERPs and pupil sizes were recorded (Kuipers & Thierry, 2013). Although the ERPs were similar between the two language groups, only bilinguals displayed a larger pupil dilation response for unrelated pictures, suggesting that bilingual children allocate more attention to unexpected linguistic information in their dominant language (Kuipers & Thierry, 2013).

In the current study, we used the ERP technique to study lexical-semantic processing in a cross-language priming task to ascertain whether words presented in one language activate words in another language, and whether these activations are equally strong for both directions of translation. In adults, the reaction times to target words preceded by equivalent translated prime words are faster than those to target words preceded by unrelated prime words, suggesting that linguistic processing in one language influences the processing in the other language (Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009). Cross-language priming effects have been obtained in both directions (forward and backward translation), but typically dominant language has more influence on non-dominant language (e.g., Alvarez, Holcomb, & Grainger, 2003; Basnight-Brown & Altarriba, 2007; Perea, Dunabeitia, & Carreiras, 2008; Dunabeitia, Perea, & Carreiras, 2010; Hoshino, Midgley, Holcomb, & Grainger, 2010; Geyer, Holcomb, Midgley, & Grainger, 2011; Schoonbaert, Holcomb, Grainger, & Hartsuiker, 2011). This asymmetrical effect has also been found in ERP studies where the N400 effect was observed only for forward translation (Hoshino et al., 2010). In some studies the N400 effect was observed in both priming directions, but it was longer lasting for forward than for backward direction (Schoonbeart et al., 2011), or it was earlier for backward than for forward direction (Alvarez et al., 2003). It has been suggested that both language proficiency and language balance in adult bilinguals affect the symmetry of the effect (Basnight-Brown & Altarriba, 2007; Perea et al., 2008; Dunabeitia et al., 2010; Geyer et al., 2011; Wang, 2012). In our study, we aimed to explore whether the N400 translation effect is obtained in developing brain and whether this effect is similar for forward and backward translation direction. Occurrence of a symmetrical N400 effect (similar effect in forward and backward translation) would indicate that the lexical-semantic links between two languages are similarly established.

2. Material and methods

2.1. Participants

Seventeen 2–4-years-olds (8 girls and 9 boys; mean age: 33 months (SD 8 months); range: from 23 months to 48 months) children participated in the experiment. The children were recruited from bilingual day care centres, schools, and associations from the Paris area. All children were born full-term and none of them suffered from hearing or language impairment. The parents gave informed consent before participation. 16 children were raised in a bilingual family where mother spoke French and father English (n = 8), or mother spoke English and father French (n = 8). In one family both parents spoke French, but their child was exposed to native English in a day care daily since the age of 6 months. Parents evaluated the amount of language exposure by estimating the number of hours their children were exposed to each language on a daily basis. Parents also estimated their child's linguistic skills separately in each language using a 5-point scale. Fourteen additional children were recruited but their data were rejected due to noisy data (n=10), or refusal to put the cap (n=4).

2.2. Stimuli

The stimuli were one-, two-, or three-syllable French basic level nouns and their English translations from ten categories (animals, clothes, body parts, food, furniture, transportation, household items, persons, nature, and buildings). The stimuli were arranged into 126 prime-target word pairs. Half of the word pairs consisted of identical translation (e.g., "ours"-bear) and half of them were unrelated words (e.g., "fromage"(cheese)-bear). Each target word was presented four times; once in both trial conditions in both languages. The mean durations of unrelated and translated *French* prime words were 666 ms and 655 ms, respectively. The mean durations of unrelated and translated *English* prime words were the same (740 ms). The mean durations of *French and English target* words were 664 ms and 738 ms, respectively. The mean number of syllables of unrelated and translated *French* prime words was 1.63 and 1.83, respectively. The syllables of unrelated and translated *English* prime words were 1.41 and 1.37, respectively. The syllables of *French* and *English* target words were 1.83 and 1.37, respectively. The phonemes of unrelated and translated *French* prime words were 4.20 and 4.37, respectively. The phonemes of unrelated and translated *English* prime words were 4.14, and 3.92, respectively. The number of phonemes of *French* and *English* target words was 4.37 and 3.92, respectively. None of the variables (durations, syllables, or phonemes) differed significantly between prime and target words (all main effects of *trial type* were > 0.05). French words had more (mean 1.73) syllables than English (mean 1.42) words ($F(1,3)=30.83$, $p < 0.001$), but they were shorter in duration (mean duration 664 ms) than the English (mean duration 741 ms) words ($F(1,3)=36.47$, $p < 0.001$).

The words were recorded and edited with Cool Edit 2000 (Syntrillium Software Corp., Phoenix, AZ) and Praat (version 5.3.02) programs. The speakers were three native French and three native American English females. The speakers were asked to pronounce the words slowly. The sound levels were normalized among the speakers and words.

2.3. Experimental procedure

Children were seated in a dimly lit room facing loudspeakers at the distance of 100-120 cm. Parents were instructed not to communicate verbally with their child during the actual experiment. Children were allowed to play with small toys positioned on the table in front of them during the experiment. The stimulus onset asynchrony (SOA) was 1200 ms between the prime and the target words in each word pair and the intertrial interval (ITI) between the word pairs was 2200 ms. Each stimulus pair (126 pairs) was presented twice during the experiment; once in French-English direction, and once in English-French direction. The whole experiment lasted about 24 minutes.

2.4. EEG Recording and Analysis

Continuous electroencephalogram (EEG) was recorded (bandpass = 0.1–100 Hz, sampling rate = 250 Hz) from 62 electrodes using a Geodesic Sensor Net (GSN, NetStation EGIS V2.0) referenced to the vertex during the acquisition. Impedances were kept below 50 kΩ. EEG was filtered (0.3–30 Hz), segmented (1000 ms, beginning 200 ms before target word onset), and ocular artefacts were removed with an ocular artefact removal (OAR) algorithm (Gratton, Coles, &

Donchin, 1983). The 200-ms pre-stimulus period determined the baseline for amplitude measures. The epochs including artefacts (eye-movements, blinks, motion artefacts exceeding ± 200 μV in any channel) were excluded. The epochs with more than 20 contaminated channels were also rejected. Individual bad channels were replaced using spherical spline interpolation. The epochs were averaged separately for each subject, type of target word (translated or unrelated) and language (French or English). The averaged waveforms were re-referenced to the linked mastoids and baseline corrected. The epochs were grand-averaged across all participants for the type of target word. The mean number of trials after the artefact rejection was 34 for translated French and 35 for translated English target words, and 33 for unrelated French and 35 for English target words.

2.5. Statistical analysis

The analysis of variance (ANOVA) including the factors *trial type* (translated *versus* unrelated target word), *target word language* (French *versus* English), recording site (frontal *versus* parietal) and *laterality* (left, midline, and right) as within-subject factors were analysed separately in 100-ms time windows. The mean amplitudes were calculated separately for each electrode (altogether 27 electrodes) in each time interval. In each recording area, the mean amplitudes that were extracted from single electrodes were averaged. The frontal and the parietal recording sites included the following electrode positions: 9, 12, 13, 15, and 16, (frontal left), 3, 4, 7, and 8, (midline frontal), 2, 57, 58, 61, and 62 (frontal right), 28, 29, 32, 33, and 37 (parietal left), 34, 38, and 39 (midline parietal), and 40, 41, 42, 45, and 46 (left parietal). According to the 10-10 international electrode position system, the electrode placements 13 and 62 in frontal area are approximately located around F3 and F4 positions, and placements 28 and 46 in parietal-occipital area around P3 and P4 positions. The statistical analyses were conducted using the SPSS statistical package (IBM SPSS Statistics, version 20) and all amplitude results of the ANOVAs were Greenhouse–Geisser corrected for non-sphericity when appropriate.

3. Results

A mean daily exposure to French and English languages estimated by parents was 62% (range 30-90%) and 38% (range 10-70%), respectively. The parents estimated also their children's language skills using a 5-point-scale as 4.2 ($SD = 0.69$) for French and 4.1 ($SD = 0.90$) for English. Only eleven participants (out of 17) had their CDIs filled. Those participants were estimated to comprehend 178 French, and 162 English words, and to produce 153 French and 135 English words. Even if estimated language skills and vocabulary sizes were comparable, we defined French to be the dominant, and English the non-dominant language because all children were living in French linguistic and social environment.

The ERPs for English (forward translation) and French (backward translation) target words are illustrated in Figures 1 A and B. The negativity was larger for translated than for unrelated target words. The main effects of trial type or target language were not significant, but the interaction between trial type, target language, and recording site was significant in 100-200 ms ($F(1,16)=5.23$, $p < 0.05$) and 300-400 ms ($F(1,16)=5.30$, $p < 0.05$) time windows. In 500-600 ms time window, the interaction between trial type and laterality was significant ($F(2,32)=4.62$, $p < 0.05$).

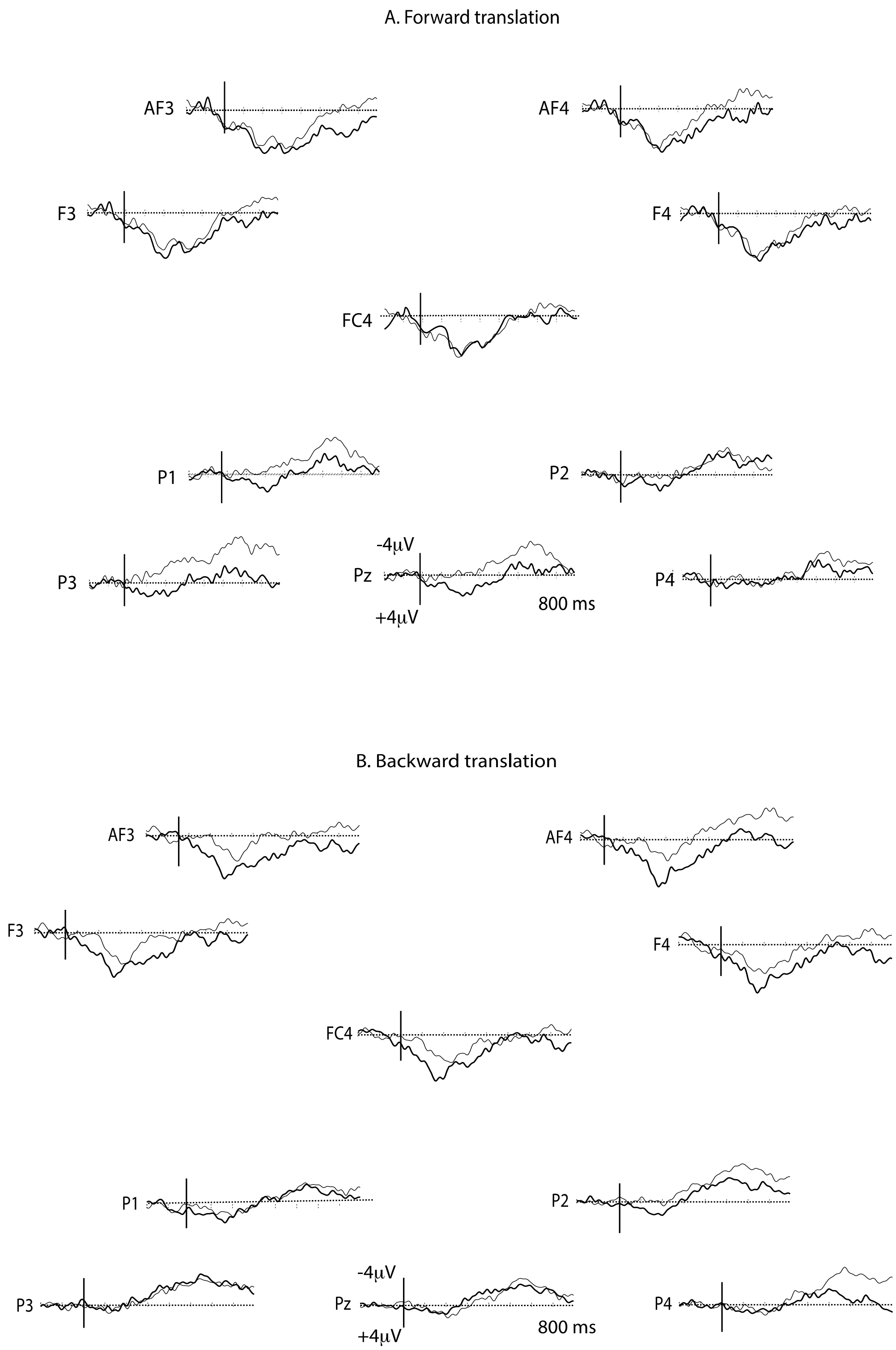


Fig. 1A-B. (A) Grand-averaged waveforms for translated (thin line) and unrelated (thick line) target words in the non-dominant language (forward translation). The N400-like effect was found over the left posterior recording sites. (B) Grand-averaged waveforms for translated (thin line) and unrelated (thick line) target words in the dominant language (backward translation). The N400-like effect was found bilaterally over the frontal recording sites. The vertical line illustrates the target word onset.

Scalp maps indicate that the N400 translation effect was locally distributed over the left posterior scalp position for forward translation whereas for backward translation, the effect was more widely distributed over the frontal scalp positions (Fig. 2).

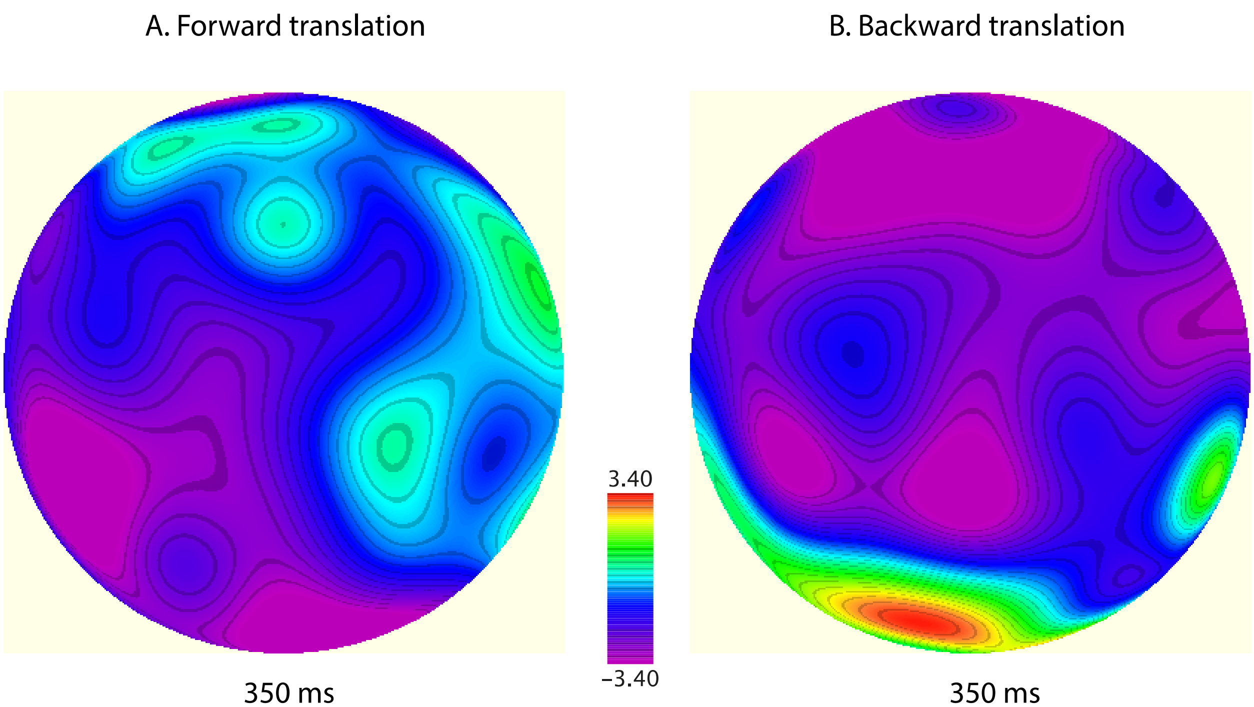


Fig. 2A-B. Topographical maps illustrating the subtraction of the unrelated condition from the translated condition during (A) forward and (B) backward translation at 350 ms after the onset of the target word.

4. Discussion

The results showed that the N400-like translation effect occurred in a cross-language priming task in bilingual 2–4 years old toddlers. The effect was obtained both in the forward and backward priming directions but the scalp distribution depended on the target word language. For forward translation, the effect was obtained over the left posterior recording sites, whereas for backward translation, the effect was bilaterally distributed over the frontal recording sites. The results indicate that prime words both in dominant and non-dominant languages activate target words in a cross-language priming task, suggesting that the lexical-semantic links between two languages are built during early language acquisition. However, the neural resources activated in processing of lexical-semantic information in the dominant and the non-dominant language might be segregated, as indicated by different distribution of ERPs in forward and backward translation conditions.

Our results are in accordance with earlier ERP studies on bilingual word processing showing that neural mechanisms underlying processing of dominant and non-dominant languages are not identical (e.g., Conboy & Mills, 2006; Vihman et al., 2007). In these studies, both latency and distribution differences between dominant and non-dominant languages were reported. The latencies were longer for non-dominant than for dominant language words (Vihman et al., 2007), and the ERPs were lateralized for dominant but not for non-dominant language words (Conboy & Mills, 2006). In these studies, the N200-400 components were measured in response to known and unknown words, whereas in our study, we were interested in priming effects across two languages. Recently, it was shown that priming effects in within- and cross-language priming tasks were obtained only when the primes were presented in the dominant language, suggesting that words in the non-dominant language might have weaker representations in semantic memory (Singh, 2014).

The N400 effect in monolingual children has been found over the parietal (Friedrich & Friederici, 2005**,** 2010; Rämä et al., 2013), frontal (Torkildsen et al., 2007) or both (Friedrici & Friederici, 2004) recording sites. It has been earlier shown that in younger children, the ERPs associated with processing of word familiarity were observed bilaterally and broadly distributed over the anterior and posterior recording sites (Mills, Coffey-Corina, & Neville, 1997), whereas in older children, the ERPs were larger over the left temporal and parietal recording sites (Mills, Coffey-Corina, & Neville, 1993), suggesting that language-related ERPs become more focally distributed with increasing experience with words. This suggestion is in accordance with our findings showing that during forward translation, the N400-like effect was more focally distributed over the left posterior recording sites whereas during backward translation, the effect was more broadly distributed over the frontal recording sites. It is also possible, as suggested earlier, that word representations in the non-dominant language are weaker, and thus, more attentive and cognitive resources are needed to activate semantic representations in backward translation.

The N400 component was more negative for translated than for unrelated word pairs. This finding is in contrast to earlier studies in adults, in which larger negativity was found for unrelated than for translated word pairs, indicating that when words are repeated by translation equivalents, the N400 component diminishes (e.g., Schoonbaert et al., 2010; Geyer et al., 2011). Interestingly, in adult bilinguals, the polarity was shown to reverse in a later time window (500-700 ms) in a within-language repetition task (Geyer et al., 2011) whereas in our study, the polarity was reversed during the whole recording window. This indicates that repeating a word in two languages provokes larger incongruence effect than repeating two unrelated words. There is a possibility that the reversed N400-like effect reflects the role of translation equivalents in developing bilingual lexicon. Even if bilingual children do know early in their language development that two words refer to the same concept (e.g., Nicoladis & Genesee, 1997; De Houwer, Bornstein, & Coster, 2006), the inter-individual variability is high (De Houwer et al., 2006; David & Wei, 2008). Thus, the amount of translation equivalents may vary in developing lexicon, and this may partly explain the difference in adult and developmental studies.

Altogether, our study showed that presentation of a prime word activates words in the second language in developing bilingual brain. This was indicated by a presence of the N400 translation priming effect for both forward and backward translation directions. However, the distribution of the N400 effect was different for words in the dominant and the non-dominant language, suggesting that neural representations underlying processing of two languages in bilingual brain might be segregated. This question, however, should be further investigated by measuring the distribution of ERPs in within-language priming tasks for each of the two languages.

References

Alvarez, R. P., Holcomb, P. J., & Grainger, J. (2003). Accessing word meaning in two languages: An event-related brain potential study of beginning bilinguals. Brain and Language, 87, 290-304.

Arias-Trejo, N., & Plunkett, K. (2009). Lexical-semantic priming effect during infancy. Phil. Trans. R. Soc. B, 364, 3633–3647.

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.

Basnight-Brown, D. M., & Altarriba, J. (2007). Differences in semantic and translation priming across languages: The role of language direction and language dominance. Memory & Cognition, 35, 953-965

Bialystok, E. (2009). Bilingualism: The good, the bad, and the indifferent. *Bilingualism: Language and Cognition*, *12*(01), 3-11.

Bijeljac-Babic, R., Serres, J., Höhle, B., & Nazzi, T. (2012). Effect of bilingualism on lexical stress pattern discrimination in French-learning infants. PloS one, 7(2), e30843.

Bosch, L., & Sebastián-Gallés, N. (1997). Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. Cognition, 65(1), 33-69.

Bosch, L., & Sebastián-Gallés, N. (2001). Evidence of early language discrimination abilities in infants from bilingual environments. Infancy, 2(1), 29-49.

Burns, T. C., Yoshida, K. A., Hill, K., & Werker, J. F. (2007). The development of phonetic representation in bilingual and monolingual infants. Applied Psycholinguistics, 28(03), 455-474.

Byers- Heinlein, K., & Werker, J. F. (2009). Monolingual, bilingual, trilingual: infants' language experience influences the development of a word- learning heuristic. Developmental science, 12, 815-823.

Conboy, B.T., & Mills, D.L. (2006). Two languages, one developing brain: event-related potentials to words in bilingual toddlers. Developmental Science, 9, 1–12.

David, A., & Wei, L. (2008). Individual differences in the lexical development of French–English bilingual children. International Journal of Bilingual Education and Bilingualism, 11, 598-618.

Duñabeitia, J. A., Perea, M., & Carreiras, M. (2010). Masked translation priming effects with highly proficient simultaneous bilinguals. Experimental Psychology (formerly Zeitschrift für Experimentelle Psychologie), 57(2), 98-107.

Fennell, C. T., Byers- Heinlein, K., & Werker, J. F. (2007). Using speech sounds to guide word learning: The case of bilingual infants. Child development, 78(5), 1510-1525.

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.

Friedrich, M., & Friederici, A. D. (2005). Semantic sentence processing reflected in the event-related potentials of one-and two-year-old children. *Neuroreport*, *16*(16), 1801-1804.

Friedrich, M., & Friederici, A.D. (2006). Early N400 development and later language acquisition. *Psychophysiology*, *43,* 1–12.

Friedrich, M., & Friederici, A.D. (2010). Maturing brain mechanisms and developing behavioral language skills. Brain and Language, 114, 66-71.

Geyer, A., Holcomb, P. J., Midgley, K. J., & Grainger, J. (2011). Processing words in two languages: an event-related brain potential study of proficient bilinguals. Journal of neurolinguistics, 24(3), 338-351.

Gratton, G., Coles, M.G.H., & Donchin, E. (1983). A new method for off-line removal of ocular artifacts. Electroencephalography and Clinical Neurophysiology, 55, 468–484.

Hoff, E., Core, C., Place, S., Rumiche, R., Señor, M., & Parra, M. (2012). Dual language exposure and early bilingual development. *Journal of child language*, *39*(01), 1-27.

Hoshino, N., Midgley, K. J., Holcomb, P. J., & Grainger, J. (2010). An ERP investigation of masked cross-script translation priming. Brain research, 1344, 159.

De Houwer, A., Bornstein, M. H., & De Coster, S. (2006). Early understanding of two words for the same thing: A CDI study of lexical comprehension in infant bilinguals. International Journal of Bilingualism, 10(3), 331-347.

Kuipers, J. R., & Thierry, G. (2012). Event-related potential correlates of language change detection in bilingual toddlers. *Developmental cognitive neuroscience*, *2*(1), 97-102.

Kuipers, J. R., & Thierry, G. (2013). ERP-pupil size correlations reveal how bilingualism enhances cognitive flexibility. *Cortex*, *49*(10), 2853-2860.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual review of psychology*, *62*, 621-647.

Mills, D. L., Coffey-Corina, S. A., & Neville, H. J. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *Journal of Cognitive Neuroscience*, *5*(3), 317-334.

Mills, D. L., Coffey- Corina, S., & Neville, H. J. (1997). Language comprehension and cerebral specialization from 13 to 20 months. *Developmental Neuropsychology*, *13*(3), 397-445.

Nicoladis, E., & Genesee, F. (1997). Language Development in Preschool Bilingual Children. Journal of speech Language pathology and audiology, 21(4), 258-270.

Oller, D., Eilers, R. E., Urbano, R., & Cobo-Lewis, A. B. (1997). Development of precursors to speech in infants exposed to two languages. Journal of child language, 24(02), 407-425.

Pearson, B. Z., Fernandez, S. C., & Oller, D. K. (1993). Lexical development in bilingual infants and toddlers: Comparison to monolingual norms. Language learning, 43(1), 93-120.

Perea, M., Duñabeitia, J. A., & Carreiras, M. (2008). Masked associative/semantic priming effects across languages with highly proficient bilinguals. Journal of Memory and Language, 58(4), 916-930.

Petitto, L. A., Katerelos, M., Levy, B. G., Gauna, K., Tétreault, K., & Ferraro, V. (2001). Bilingual signed and spoken language acquisition from birth: Implications for the mechanisms underlying early bilingual language acquisition. Journal of child language, 28(02), 453-496.

Poulin-Dubois, D., Bialystok, E., Blaye, A., Polonia, A., & Yott, J. (2013). Lexical access and vocabulary development in very young bilinguals. International Journal of Bilingualism, 17(1), 57-70.

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.

Singh, L. (2014). One World, Two Languages: Cross- Language Semantic Priming in Bilingual Toddlers. *Child development*, *85*(2), 755-766.

Schoonbaert, S., Duyck, W., Brysbaert, M., & Hartsuiker, R. J. (2009). Semantic and translation priming from a first language to a second and back: Making sense of the findings. Memory & Cognition, 37(5), 569-586.

Schoonbaert, S., Holcomb, P. J., Grainger, J., & Hartsuiker, R. J. (2011). Testing asymmetries in noncognate translation priming: Evidence from RTs and ERPs. Psychophysiology, 48(1), 74-81.

Styles, S. J., & Plunkett, K. (2009). How do infants build a semantic system? Language and cognition, 1-1, 1–24.

Torkildsen, J. 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.

Torkildsen, J.K., Syversen, G., Simonsen, H.G., Moen, I., & Lindgren, M. (2007). Electrophysiological correlates of auditory semantic priming in 24-month-olds. Brain & Language, 20 (4), 332-351.

Vihman, M. M., Thierry, G., Lum, J., Keren-Portnoy, T., & Martin, P. (2007). Onset of word form recognition in English, Welsh, and English-Welsh bilingual infants. Applied Psycholinguistics, 28(3), 475.

Wang, X. (2012). Language dominance in translation priming: Evidence from balanced and unbalanced Chinese–English bilinguals. The Quarterly Journal of Experimental Psychology, 66, 727-743.

Weikum, W. M., Vouloumanos, A., Navarra, J., Soto-Faraco, S., Sebastián-Gallés, N., & Werker, J. F. (2007). Visual language discrimination in infancy. Science, 316(5828), 1159-1159.

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 1-23.

General discussion and perspectives

Summary of results

The aim of the current thesis was to investigate whether the developing lexical system is organized by taxonomic categories, and whether dual language experience has an effect on this organization.

The results of Study I showed that the N400 priming effect occurred in 24-month-olds over the right parietal-occipital recording sites. In 18-month-olds the effect was observed similarly to 24-month-olds but only in those children with high productive skills, suggesting that words are taxonomically organized in the developing lexical-semantic system at the age of two years and even earlier in children with high productive skills.

Study II revealed that semantic priming effects occurred in 18-month-olds, independently of the children's productive skills. This finding suggests that children are sensitive to taxonomic relationships between words prior to their second birthday. Our results showed also that both automatic activation and controlled processes contribute to the priming effects. These contributions were reflected by modulations of priming effects and language-related ERPs. Three components, N2, N400, and LPN, were modulated by semantic relatedness but only N2 and LPN were also sensitive to the SOA length. The frontally distributed N2 was more pronounced at the long than at the short SOAs, suggesting that that controlled processes are involved in generating the N2 priming effect. The lateralization of the LPN varied across SOAs. At the short SOA, priming effect was more prominent over the right hemisphere whereas at the long SOA it was more prominent over the left hemisphere. These findings suggest that both automatic activation and controlled processes contribute to priming effects during language development, but the neural resources underlying these processes might differ.

The results of Study III showed that, in a looking while listening task, the presence of a semantic competitor, sharing different amount of features, interfered with word recognition. Children were more likely to look at the named target in the unrelated than in distant competitor condition. In the near competitor condition, looking times were equally distributed among the target and the distracter. The likelihood of fixating the competitor was affected by the degree of its semantic feature similarity with the target. These findings suggest that taxonomically related words are organized according to their semantic similarity distances and that this organization affects word recognition in a graded manner.

The preliminary results of Study IV showed that in 2-4 years old French (dominant)-Spanish (non-dominant) bilinguals, semantic priming effects occurred for both the dominant and the non-dominant language but the distribution of ERPs varied according to the processed language. The frontally distributed N2 was left-lateralized for French, while for Spanish it was right-lateralized. Over the posterior recording sites, the N400 was symmetrically distributed for French, whereas for Spanish, the effect was more focal over the right hemisphere.

Study V showed that words processed in one language activate their lexical-semantic representations in the other language and vice versa. The N400 was more negative for translation equivalents compared to taxonomically unrelated target words in both languages. However, the distribution of the N400 effect depended on the direction of translation. For forward translation (L1 to L2) the effect occurred over the posterior recording sites whereas for backward translation (L2 to L1) the effect appeared over the frontal region.

The results of these two studies indicate that even when both languages are acquired from birth, distinct neuronal resources might underpin word processing in the dominant and non-dominant languages.

1. Taxonomically organized lexicon during early language development

The findings of Study I demonstrated that words are taxonomically organized in the developing lexical-semantic system at 24-months of age, and even earlier, at 18-months, in children with enhanced productive vocabulary. The occurrence of semantic priming effects indicates that children seem to understand that *carrot* and *strawberry*, for example, are linked together. Even though children were not tested on their knowledge of superordinate terms (e.g., ‘animals’, ‘clothes’, ‘food’), they relate words that are drawn from the same taxonomic category to each other. In line with recent cross-modal studies, these results indicate that 24-month-old children, but not younger integrate words into a semantic system that encodes relatedness between them (Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2009, 2013). The fact that priming effects were obtained even when no visual referent was presented, indicates that when processing spoken language, children are able to represent the existing semantic relationships between words (Torkildsen et al., 2007; Willits et al., 2013).

While at 24-months the vocabulary size did not contribute to the magnitude of semantic priming, at 18-months it did. At 24-month-olds, the magnitude of priming did not differ across both vocabulary groups (low and high producers), suggesting that priming effects may no longer depend on the child's expressive skills. This might be simply due to the fact that at 24-months, children know more words since their lexicon has been enlarged earlier during the vocabulary spurt phase. On the other hand, at 18-months, priming effects occurred only in those children with high productive skills, suggesting that enhanced vocabulary contribute to the taxonomic organization. The difference between high and low producers might be due to their differences in speed of word processing. This hypothesis is consistent with previous studies suggesting that enhanced vocabulary induces faster processing and greater efficiency in spoken language processing (e.g., Fernald et al., 2002, 2006). The absence of priming effects in the low producers group may be also due to weaker activation of the lexical-semantic representations, as they have poorer lexicon than the high producers.

The absence of semantic priming effect in the whole 18-month-olds group is in line with previous findings demonstrating that priming effects do not occur at 18-months (Styles, Arias-Trejo, & Plunkett, 2008; Styles & Plunkett, 2009; Arias-Trejo & Plunkett, 2009), suggesting that word meanings may be learnt independently one from another without being linked. For example, an 18-month-old child understands the words *dog* and *cat* and the objects to which they refer, but their lexicon might be still organized according to 'one-to-one' associations (Arias-Trejo & Plunkett, 2009). It means that the semantic relationship between them is not yet established; hearing the word *dog* does not activate yet *cat*, and vice versa. The fact that 21-month-olds but not 18-month-olds exhibited priming effect (Arias-Trejo & Plunkett, 2009, 2013) even when both prime and target words shared phonological onset (Styles et al., 2008) suggest that the lexicon inter-connectivity emerges between 18- and 21-months, a period related to the vocabulary growth (Styles et al., 2008). However, in Arias-Trejo and Plunkett (2009) study, priming effects at 18-months occurred under specific circumstances, where prime and target words were repeated (repetition priming task). The authors interpreted this finding as evidence of an emerging sensitivity to related meanings. They further suggested that the absence of priming effects in the taxonomic-associative priming condition might also be due to methodological constraints. For instance, in their primed IPL tasks, the SOA was either 200 ms or 400 ms. Since 18-month-old children are considered to be slower than 21- and 24-month-olds, in processing words (Fernald et al., 1998, 2006), the activation of the target word from the onset of the prime, may take longer time (Arias-Trejo & Plunkett, 2009).

Nevertheless, Study II showed that priming effects were obtained for the whole group of 18-month-old participants, independently of their vocabulary skills, demonstrating sensitivity to semantic relatedness already at this age. The occurrence of semantic priming in this study suggests that words are taxonomically organized prior to the second birthday and even before entering the vocabulary spurt. This finding is in line with a recent HPP study that explored whether 18-month-old children access word meanings from a continuous sequence of words and whether a spoken word would trigger the activation of its semantically related word (Delle Luche et al., 2014). Their results showed that 18-month-old children listen longer to a list containing taxonomically related words than to a list containing unrelated words. Longer listening to related words was correlated with increasing receptive but not productive vocabulary skills, suggesting that semantic relationships between words are influenced by the former rather than by the latter.

The differences between the results obtained in the previously mentioned behavioral studies (Arias-Trejo & Plunkett, 2009, 2013; Styles et al., 2008, 2009), Study I, and Study II might be related to methodological issues. In Study I, even though the ISI was constant, the SOA length varied across trials, being shorter or longer in some trials. It may be that 18-month-old high producers were able to process word pairs even with the shortest SOA, as it has been previously suggested that enhance productive vocabulary increases speed and efficiency of word processing (Fernald et al., 2006). However, in previous LWL task, 18-month-olds, low producers included, successfully recognized familiar words even with only partial acoustic information presented (=300 ms of the spoken word; Fernald et al., 2001). In Study II, all participants were considered as ‘low producers’ since they produced fewer than 50 words, and the SOAs were invariant. Although the priming paradigm was similar in both Study I and Study II, few experimental modifications were applied to Study II that might explain the differences in the results. In Study I, there were 36 target words and each target word was repeated in total four times (e.g., in related and unrelated conditions repeated twice during the experimental session). In Study II, there were more target words (e.g., 48) but each target word was repeated only twice at each SOA. Presenting children with more words and increasing the SOA length might have increased the activation of lexical-semantic representations, thereby, inducing priming effects. Recently, in a cross-modal semantic priming task, 9-month-old infants displayed an N400 effect despite a long delay (≥ 2 seconds) between the spoken word, uttered by the mother, and the appearance of the object on the visual display (Parise & Csibra, 2012). This finding indicates that infants extracted meanings from the stimuli, and the long SOA provided them with sufficient time to establish a semantic link between them. This suggests that a link between meanings of words and their referents may be established even before infants reach their first birthday (Parise & Csibra, 2012). This is in line with a recent behavioral study showing that 6- to 9-month-olds direct correctly their gaze to the named target (Bergeson & Swingley, 2012). However, in both of these two mentioned studies, a variant was added to the each experiment, that is, the mother's voice in a social interaction context. According to the authors, this experimental manipulation provided an optimal environment for measuring semantic processing. Whether the mother's voice enhances the occurrence of the N400 effect in auditory priming tasks, remains to be investigated.

2. Taxonomic categories as organized by semantic similarity distances

Together with earlier behavioral studies, the findings of Study I and II demonstrated that words are taxonomically organized and become integrated into a lexical-semantic between 18- and 24-months of age. However, in the previously mentioned primed IPL tasks, semantic relationships (e.g., associative, taxonomic, or both combined) between the prime and the target words were manipulated and target and distracter images were systematically unrelated, semantically, phonologically, and perceptually. In Study I and II, spoken word pairs were drawn either from the same taxonomic category or from two different taxonomic categories. Also, in a cross-modal priming task, violations of relationships between word-picture pairs were either within-category (e.g., dog-horse), or between-category (e.g., dog-car). Yet, none of these behavioral and ERP studies controlled or manipulated the semantic similarity distance between taxonomically related words, even in the within-category violations condition. Our following question was whether at 24-months, words are organized in taxonomic categories according to similarity distances based on the amount of their shared features. To answer this, the semantic relationship between the target and competitor images was manipulated. To our knowledge, only one study manipulated the semantic relatedness between the target and the competitor images (Arias-Trejo & Plunkett, 2010), in order to investigate the effect of categorical and perceptual similarities on word recognition. In that study, 18- to 24-month-old children looked equally the target and competitor images only when items were taxonomically related and perceptually similar (e.g., cup – bowl). This finding suggests that the presence of a semantically similar competitor induces a semantic competition and interfere with the target word recognition. It also demonstrates the advantage of perceptual dissimilarity between concepts. Still, whether the developing lexical-semantic system is organized according to similarity distances and whether this organization affects word recognition needs further investigations. Recall, in adults, it has been suggested that the lexical-semantic system is organized according to the degree of features overlap (e.g. McRae et al., 2005; Mirman & Magnuson, 2008). That is, two concepts are considered as similar based on features they have in common (e.g., categorical, perceptual (shape or color), or functional). The more features both concepts share in common, the more similar they are. The term 'feature overlap' may be applied when two items reach the maximum amount of features, thereby being highly similar. Hence, the semantic similarity effect is expressed by faster recognition of highly similar compared to less similar or unrelated pairs of stimuli.

Whether feature-based organization underpin the structure of the developing lexical-semantic system language development and whether this organization affects toddlers' word recognition was explored in Study III. This was studied by presenting simultaneously two images, the target and its semantic competitor, illustrating objects that were drawn from the same taxonomic category, sharing in common different amount of features, such as taxonomic, perceptual, and functional. The results of Study III revealed that 24-month-old children looked longer at the named target in the distant and unrelated competitor conditions. In the near competitor condition, children looked equally both the target and the competitor. This latter response might be due to the perceptual similarities, since visual similarities (such as shape or color) between two items were suggested to induce conceptual competition at 18- and 24-month-olds (Arias-Trejo & Plunkett, 2010). Thus, the possibility that equal looking times in the near competitor condition are driven by perceptual similarities was not excluded.

Let us discuss first the effect of high conceptual and perceptual similarities on word recognition. It has been earlier suggested that when representations of word meanings are not well established during the second and third year of life, children tend to overextend a known word to other referents, especially when children are presented with an unknown object. These overextensions are thought to be driven by 'shape bias' and perceptual features (Clarck, 1973; Thomson & Chapman, 1976). In the near competitor condition of Study III, looking times were equally distributed between the target and competitor images, indicating that the simultaneous presence of the competitor interfered with word recognition. Similar results were found in Arias-Trejo & Plunkett (2010). Thus, it can be assumed that at 24-months children still overextend known words based on perceptual similarities between items. For instance, equal looking at *cow* and *sheep*, in our study, could be interpreted as overextension of one of the items. However, if children did not know one of the items, we should have observed a preference to one of the images in the pre-naming phase, which was not the case. Because, only trials in which children looked both the target and the competitor images were included in the statistical analyses. Trials in which children looked only one of the images in the pre-naming phase were excluded. Also, if children were overextending, no preference of target looking in post-naming phase should have been observed even in distant competitor condition. But, the results revealed graded increased target looking times in the distant competitor condition. Often, objects belonging to the same taxonomic category are perceptually similar, and it has been suggested that perceptual similarities, such as shape, predict the taxonomic sensitivity (e.g., Poulin-Dubois, Frank, Graham, & Elkin, 1999). The authors suggest that shape is a salient information used by the children when extending to novel referents from the same taxonomic category. On the other hand, it was argued that even if shape is a salient aspect of an object, it does not underline word representations (Gelman, Croft, Fu, Clausner, & Gottfried, 1998).

Another feature that might drive word recognition is colour matching based on prototypical representations. It has been recently shown that 2- to 3-year old children are likely to fixate colour matched items when the named referent is absent (e.g., Johnson, McQueen, & Huettig, 2011; Johnson & Huetting, 2011). For instance, upon hearing the prime word *frog*, while looking at green ball and another colour mismatching objects, children are likely to fixate the green ball. These findings suggest that children generate associated features, such as the colour *green*, and detect the object on the visual display overlapping with this feature. However, when presented with a colour match (e.g., yellow cup) and a taxonomically related object (e.g., cookie) to the prime (e.g., banana), children are faster and look earlier at taxonomically related object compared to the colour match object (Mani, Johnson, McQueen & Huettig, 2013). Also, 24-month-old children were shown to look longer at a semantically related item (e.g., monkey) when the named target (e.g., dog) was absent (Johnson et al., 2011). These results suggest that semantic knowledge is a salient aspect that contributes to the establishment of the lexical-semantic structure.

A second alternative for equal looking in the near competitor condition can be proposed, namely, the semantic competition. In Arias-Trejo & Plunkett (2010), children were more likely to fixate the named target word (e.g., apple) when presented simultaneously with a competitor perceptually similar but drawn from different semantic category (e.g., ball) compared to when it was presented with a categorically and perceptually similar competitor (e.g., orange). This result indicates that interference with target word recognition is driven by semantic rather than by visual similarity and strengthens the hypothesis of semantic competition. Also, in adults, it has been shown that looking to the competitor is driven by semantic rather than perceptual similarities (Huettig & Altmann, 2005; Yee & Sedivy, 2006; Mirman & Magnuson, 2008, 2009). This was demonstrated by creating a model of growth curve analysis (GCA; Mirman & Magnuson, 2009). The authors asked participants to rate the semantic and visual similarity between the target and the near, and between the distant and unrelated competitors. The GCA by items is based on the proportion of fixations to the target. The results showed that rates of visual similarity improved the model fit. When rates of semantic similarity were added to the model containing already the visual similarity, they provided a significant improvement, accounting for additional variance. The GCA revealed that looking times to the semantically similar competitor were higher than looking times to the visually similar competitor. Accordingly, in Study III, equal looking times to the competitor and the target in the near condition might be due to a strong activation of the former when the latter was being processed. The degree of competition was reflected by graded responses from the near to distant and to unrelated conditions. These graded responses reflect also the dynamics of words activation in the lexical-semantic system when processing a spoken word. The results obtained fit well to the distributed memory model, presuming that as a word is processed activation spreads between features (e.g., Masson, 1991). Therefore, it can be inferred that words are linked to each other not only based on taxonomic relationships but also by feature similarities, reflecting thus a graded organization. The fact that children could not disambiguate the target and competitor objects in the near competitor condition might be due to the maximized features overlap between them.

The semantic competition in Study III was also reflected by the time course. Across time, the differences in target looking proportions between distant and unrelated conditions were observed earlier than between near and distant conditions. The time course analysis revealed that the three conditions deviated from one another from ~1000 ms after the spoken target onset onward, to ~2000 ms. These findings reveal that the temporal dynamics of semantic activation reflects a graded similarity distance between the items. Our time courses are similar to those previously reported in young children (Arias-Trejo & Plunkett, 2010; Johnson et al., 2011; Mani et al., 2013), but differ from those found in adults (e.g., Mirman & Magnuson, 2009). Our participants looked at the target images less in the near than in the unrelated condition during the whole trial, indicating that semantic competitor effect was longer lasting than in adults. The visual inspection of the time course analysis in Arias-Trejo and Plunkett (2010) demonstrates also that the semantic competition in the high conceptual and perceptual similarity condition lasted the whole trial. In Johnson et al. (2011), 24-month-olds looked to the distracter image that was either colour-related or semantically-related to the named absent target in the 1000-2000 ms time interval. But, the time course of activating the colour and semantic knowledge did not differ. However, Mani et al. (2013) did find a significant difference in the time course of colour-matching and semantic-matching conditions. In the prime window (onset of the prime to the onset of the named target), children were more likely to look at the semantically-related target compared to the colour-related target whereas looking to the colour-matching increased later, in the target window (0-1000 ms post-naming). These findings are in accordance with the hypothesis that word recognition is more affected by semantic features overlap than by perceptual features. As in Study III, these findings suggest that activation of the lexical-semantic network occurs about one second from the spoken target word onset. On the other hand, adults look systematically more to the target than the near or distant competitor, but they show transient, increased looking to near or categorical competitors at the beginning of the trial. In future studies, it remains to be investigated whether the time course of activation would be similar to adults' when more items are presented simultaneously on the visual display.

Another question of interest is whether the acquisition of a second language at early childhood affects this graded semantic similarity organization in the bilinguals' first language (L1). Earlier, it has been shown that bilingual infants reach their language milestones within the same age as their monolingual counterparts (e.g., Pearson et al., 1993; Kovelman, Baker, & Petitto, 2008). As for the lexical development, it has been shown that preschool and school aged bilingual children have smaller vocabulary size in L1 compared to their monolingual counterparts (e.g., Bialystok et al., 2010). However, total receptive and expressive vocabulary in both languages (L1 and L2) at younger ages (≤ 3 years) was found comparable to that of monolinguals (e.g., Marchman et al., 2009; Pearson et al., 1993). The differences between both linguistic groups appear when expressive skills are separated for both languages, resulting in fewer words in the bilinguals' L1 and L2. Yet, the question of whether the developing lexical-semantic system is organized in bilinguals' L1 as in monolinguals, that is, according to semantic similarity distances, has not been earlier studied. Moreover, if bilingual children were to have fewer words in L1 compared to monolinguals, could it be expected that expressive skills in L1 contribute to this organization anyhow? These questions and their answers are the basis of what we are currently investigating.

3. Cognitive mechanisms involved in lexical-semantic processing

The results of Study II showed that ERPs in response to spoken target words were modulated not only by the preceding semantic information (e.g., related *versus* unrelated prime words) but also by the SOA length. In adults, it has been shown that the engagement of controlled processes increases the magnitudes of the N400 effect at long SOAs (e.g., Hill et al., 2005), suggesting that automatic activation process is limited to short SOAs. That is, longer time-interval between the prime and target words allows deeper semantic integration, thereby augmenting the amplitudes of the N400 priming effect. Here, controlled processes modulated the magnitudes of the N2 and the distribution of the LPN, but no modulations were found for the N400. The N2 priming effect was more prominent at the long than at the short SOAs. This leads to the assumption that when words are separated by longer time (> 1000 ms), controlled processes are engaged (expectancy or post-lexical matching). At the short SOA the LPN was right-lateralized, reflecting automatic activation process, whereas at the long SOA it was left-lateralized, suggesting that controlled processes were engaged. To our knowledge, no other developmental study has investigated the cognitive mechanisms underlying semantic processing and further studies are needed to clarify this issue.

The fact that the magnitude of the N400 priming effect was not modulated by the SOA in Study II, might indicate that controlled processes are not yet well established or do not contribute to deeper semantic integration at 18-months. In adults, it has been previously shown that increasing the SOA augments the N400 priming magnitudes. On the other hand, Deacon et al. (1999) suggested that automatic activation process might not decay even after 2 seconds SOA. Therefore, the absence of the long SOA effect on the N400 amplitudes might indicate that only automatic activation process was involved in generating the N400. The fact that controlled processes modulated the other components (N2 and LPN) but not the N400, indicates that even longer time (<1600 ms) may be needed for the controlled processes to get involved and modulate its magnitude.

In Study II, only the SOA length was manipulated but the number of related trials was equally distributed across SOA conditions. In adults, it has been shown that increasing the proportion of related word pairs (e.g., 75% *versus* 25%) increases the engagement of controlled processes (e.g., Hutchison, Neely, & Johnson, 2001; Bodner & Masson, 2003). Participants detect that within an experimental block there are more related than unrelated word pairs and develop an expectancy strategy by orienting intentionally their attention to these pairs. By increasing the SOA and the proportion of related word pairs the hypothesis that controlled processes contribute to semantic processing would be strengthened.

Another question of interest is whether automatic activation and controlled processed contribute to the auditory semantic processing in bilingual children. It has been previously shown that the development of executive functions is enhanced in bilinguals, even prior to their first birthday (e.g., Kovacs & Mehler, 2009; for an extensive review, see Barac, Bialystok, Castro, & Sanchez, 2014). Furthermore, bilingual infants face one of the cognitive challenges (amongst others) that consists of alternating between two languages on a daily basis, an exercise that contributes to an enhanced cognitive control. Thus, it might be assumed that in bilingual children controlled processes are developed and may contribute to the modulations of the N400 as in adults. This hypothesis is, at present, under investigation.

4. Two languages, one mind

4.1. Assessing bilingualism

A major concern in studies with bilingual toddlers is that proficiency in each of the languages cannot be evaluated for there are no objective standards and no common tests to establish the bilingual development (Bedore, Peña, Summers, Boerger, Resendiz, Greene, Bohman, & Gillam, 2012). Also, children growing up bilingually do not yet master one of the languages and large inter-individual variabilities exist in terms of languages input and output. For that reason, the creation of an objective bilingual assessment seems difficult. In developmental studies, researchers generally develop laboratory specific questionnaires regarding language history and background. Still, in some cases parents express difficulties in estimating their children's bilingualism, mainly because of changes in linguistic environment that may occur during childhood. For that reason, most of the studies on bilingual toddlers emphasize their measures on language dominance, that is, the language to which the child is mostly exposed (Grosjean, 2010). Even though early bilinguals acquire both languages from birth (simultaneous bilinguals or 'bilinguals first language acquisition' (De Houwer, 2009)), balance in both is rarely obtained (Baker, 2011). Dominance might evolve (e.g., immigration, integration into a monolingual or a bilingual school) and therefore when evaluating toddlers' bilingualisms, different factors are to be considered, such as age of first exposure, amount of language input and output, or the ability to use the two languages according to a given domain (e.g., L1 at home and L2 outside). In the bilingual studies presented in the current dissertation, questions concerned the actual situation and attempted at evaluating the total time (in percentage) the child is exposed to each language. The aim of this questionnaire was to help estimating the dominance in each language. Although participants in Studies IV and V were exposed to both languages from birth on a daily basis and parents in general expressed the desire to maintain a balanced exposure, children were living in a French dominant environment: Most of the children went to day care or school where they were exposed only to French language. Therefore, in both studies, French was estimated as the dominant language and English or Spanish as the non-dominant language.

4.2. Within-language semantic processing

Recently, it has been shown that semantic priming effects occur for the dominant but not for the non-dominant language (Singh, 2014). In that primed IPL study, 31-month-old bilinguals were reported to have both Mandarin and English as native languages. Even so, children exhibited a target preference only when the prime and target words were in the dominant language. The author suggested that the absence of priming in L2 might be due to differences in terms of lexical-semantic representations. Semantic links between words in L1 are stronger than those in L2. As a consequence, words in L1 are processed more efficiently compared to words in L2. Here, in spite of the unbalanced exposure to each of the languages, Study IV revealed that semantic priming effects occurred for both the dominant and the non-dominant languages. Bilingual children displayed frontally distributed N2 and posterior N400 priming effects for French and for Spanish. However, the distribution of the language-related ERPs varied across languages. Over the frontal recording sites, the N2 effect was left-lateralized for French, whereas for Spanish it was right-lateralized. The posteriorly distributed N400 was symmetrically distributed for French but more prominent over the right for Spanish. These results suggest that words are organized taxonomically in both languages but separate neural systems mediate each language. These results are in line with previous findings with bilingual adults (Hahne, 2001; Hahne & Friederici, 2001). During sentence comprehension task in the visual modality, the N400 in response to semantically incorrect sentences in L2 was more pronounced over the right than the left hemisphere. On the contrary, in Conboy and Mills (2006), 19- to 22-month-old bilinguals displayed a frontal N200-400 that was prominent over the right compared to the left hemisphere for the dominant language and no such asymmetry was found for the non-dominant language. The differences in terms of ERPs distribution between both populations might pertain to methodological issues. In adults, priming tasks are presented mostly in the visual modality and it has been previously shown that in lexical-decision tasks, the N400 priming effect appears over the centro-posterior recording sites with a right hemispheric bias (e.g., for a review, see Kutas & Federmeier, 2011). In toddlers' studies, ERPs are often measured in response to spoken words and the distribution and/or lateralization of language-related ERPs is still unclear. This might be due to developmental ongoing changes, such as brain maturation and vocabulary growth.

In Study IV, components of interests (N2 and N400) associated with a time-window of interest were analyzed. We applied mean amplitudes analysis, rather than peaks analysis, a method that does not allow us to determine whether peak latencies differ across the two languages. It has been earlier shown that peaked activity is typical of adult ERPs but not of infants' (for extensive review, see de Haan, 2013)). The ERPs during the first years of life (up to ~4 years) are characterized by slow wave activities with small amplitudes. For that reason, mean amplitudes rather than peak amplitudes and latencies were measured. Still, further studies are required to better understand the within-language semantic processing during language acquisition and which factor, dominance or total vocabulary size, affects more semantic priming effects.

4.3. Cross-language priming

In 2-4 year-old French-English participants, the N400 priming effect was symmetrical in both directions of translation even though its distribution varied. For forward translation, the effect was found over the left posterior recording sites, whereas for backward translation, the effect was frontally distributed. These results demonstrate that processing one language activated translation equivalents in the other language and vice versa, suggesting that lexical-semantic representations between both languages are linked and integrated into a shared conceptual system. These findings might fit into the BIA-d model (Grainger, Midgley, Holcomb, 2010) that describes the vocabulary acquisition in the second language. According to this model, as a word in L2 is learnt, it is first translated into L1, before a semantic representation of that new word is constructed. Once the links between lexical and semantic representations in L2 are strengthened, words are integrated into a shared lexical-semantic system. Furthermore, increased L2 vocabulary size contributes to the autonomy of that language which reduces the asymmetries in priming effects. However, this model describes the progressive integration of L2 into the conceptual system after the L1 has been acquired and mastered. Thus, our findings cannot fit perfectly this model since children raised bilingually learn both vocabularies simultaneously and it can be assumed that vocabularies in L1 and L2 are directly integrated into a shared conceptual system, even before one of the languages has been mastered. In line, the findings of Study V show that both languages are autonomic and as a word in one language is processed, its semantically related representation in the other language is activated and vice versa. On the contrary, Singh (2014) found an asymmetrical priming effect in early simultaneous bilinguals. Priming effects were found when primes were in L1 and target in L2 but not vice versa, suggesting that this asymmetry might be related to the dominance in each of the languages.

Nevertheless, to further strengthen the above-mentioned findings, further studies including larger sample of bilinguals are needed. Because, the main issue reported in bilingual children studies is the big variability between subjects in terms of their vocabulary skills in both languages and in their linguistic environment. In Study V, we were unable to measure the effect of receptive or productive skills in each language. The sample size was small and the age of participants varied from 2- to 4-years old. Therefore, it seemed unreasonable to analyse to effect of vocabulary skills for it would have increased the inter-individual variability.

5. ERPs and language processing during early linguistic acquisition

5.1. N2 component

The N2 component has been previously associated to familiarity effect (e.g., Mills et al., 1993, 1997), being more pronounced to words children were reported to know compared to unknown words. Familiarity with words was based upon parental reports. The N2 has also been associated to automatic orientation towards familiar words (Thierry et al., 2003). In that study, the authors interpreted the N2 as the MMN-like response, since in their experimental blocks, only 25% familiar words were included among 75% unfamiliar words. Consequently, as a familiar word was presented, the attention of 11-month-old infants was captured rapidly by that word, after 250 ms from the word onset. In addition, at 20-months, the N2 occurred during learning novel word-object pairing (e.g., Mills et al., 2005) and to violations of these newly learnt pairings (Torkildsen et al., 2008). At 24-months, the N2 was associated to the processing of acoustic-phonological information of expected target word (e.g., Friedrich & Friedrici, 2005b; Torkildsen et al., 2007). In some studies the N2 was found over the frontal recording sites (e.g., Thierry et al., 2003; Friedrich & Friedrici, 2005b; Torkildsen et al., 2007) while in others, the N2 was broadly distributed across the scalp (Mills et al., 2005; Torkildsen et al., 2008).

In Study I and II, a frontally distributed negativity at 18-months was more pronounced for unrelated compared to related target words, suggesting that it might also be associated with lexical-semantic processing. The amplitudes of the N2 were more pronounced at the long compared to the short SOA, indicating further that controlled processes might be involved in the generation of the N2 component. The fact that N2 amplitudes were modulated by the SOA at 18-months demonstrates also the engagement of attentional resources and a deeper semantic integration. Inversely, the N2 was more prominent for related than for unrelated target words at 24-months. As it was previously suggested by Mills et al. (1997), changes in language-related ERPs amplitudes and distribution may be explained by developmental factors, such as brain maturation and vocabulary growth over the second year, that contribute to a more focal distribution of priming effects. For example, in Mills et al. (1993, 1997), the N2 at 13- and 17-months was broadly distributed, but at 20-months, the effect was limited to the left temporal and parietal recording sites. Similarly, in Studies I and II, the negativity was broadly distributed at 18-months but at 24-months, the negativity in response to unrelated target words was limited to the right posterior recording sites.

In Study IV, the N2 was obtained in response to target words for both bilinguals' languages, suggesting that lexical-semantic processing does not differ across languages. A left hemispheric bias for semantic relatedness was observed for the dominant language while a right hemispheric bias was obtained for the non-dominant language. Consequently, and as it was previously hypothesized, we might assume that the right hemisphere is involved in language acquisition whereas activation over the left hemisphere reflects language specialization based on the amount of linguistic experience in a given language (e.g., Silverberg, Bentin, Obler, & Albert, 1979; for a review see Seliger, 1982; Mills et al., 1997; Thierry et al., 2003). Thus, increased exposure to French induces a more efficient semantic access compared to Spanish. Hence, a right lateralized effect for the non-dominant language might reflect slower on-going lexicon acquisition. Moreover, it has been suggested that in adults right hemispheric involvement occurs in response to the bilingual's less proficient language (Genesee, 1982).

Taken together, the findings of Studies I, II, and IV suggest that in monolinguals, the frontally distributed N2 is not related only to the familiarity effect but also to the lexical-semantic processing. The magnitudes of the N2 may be also modulated by controlled processes. In bilinguals, the lateralization, rather than the magnitudes of the N2, is modulated by the processed language.

5.2. Semantic processing as indexed by the N400

The N400 component has proved in numerous studies to reflect facilitation in accessing word meaning. Thus, measuring the N400 amplitudes in response to semantic information provides an insight to the developing lexical-semantic structure. The N400 priming effect was obtained in all studies presented in this dissertation. In Study I, the N400 priming effect occurred over the right posterior recording sites, whereas in Study II, the N400 was symmetrically distributed. In previous priming studies with children, several differences in terms distribution and lateralization of the N400 have been found. For instance, the N400 was observed at 14-months over the frontal and right posterior recording sites (Freidrich & Friederici, 2008). The negativity over the fronto-lateral recording sites was suggested to reflect word form recognition whereas the right posterior negativity was suggested to reflect semantic processing. Also, semantic priming appeared over the centro-parietal recording sites (Friedrich & Friederici, 2005) and in addition, over the frontal areas (Torkildsen et al., 2007). The authors suggested that the frontal engagement might reflect an enhanced image-specific semantic processing.

When processing semantic relatedness in each language separately, Study IV revealed an N400 priming effect in both languages but its distribution varied according to the language processed. The N400 appeared over the posterior recording sites. For French, it was symmetrically distributed over both hemispheres whereas for Spanish the effect was more pronounced over the right hemisphere. In cross-language priming task (Study V), the N400 priming effect was more pronounced for translation equivalents as opposed to unrelated word pairs, but the distribution depended on the direction of translation. The N400 appeared over the left posterior recording sites when primes in L1 activated target words in L2, whereas an anterior distribution was observed when primes in L2 activated target words in L1. An anterior distribution is thought to reflect attentional processes activated when processing visual and auditory stimuli and are suggested to overlap with the Nc, a component indexing stimulus recognition and engaging attention (e.g., De Haan & Nelson, 1999; Reynolds & Richards, 2005). Thus, the frontally distributed N400 might be due to increased involvement of attentional resources because of effortful semantic processing in the non-dominant language. These results strengthen the hypothesis that non-identical neural resources underlie semantic processing in both languages, confirming previous ERP findings (Conboy & Mills, 2006; Vihman et al., 2007) and that increased exposure to one of the languages contributes to its left hemispheric distribution. The findings of both studies (IV and V) suggest that even in early bilinguals, two different neural mechanisms are involved in generating the N400 semantic priming effect in the dominant and non-dominant language.

Altogether, the results of the studies presented here suggest that the N400 component during language development is functionally similar to that of adults' and reflects lexical-semantic processing. Still, it remains to be determined whether differences in distribution, across previously mentioned and present studies, are related to methodological constraints or to other factors, such as age, experience with language, or the nature of stimuli.

6. The effect of productive vocabulary skills on the lexical-semantic organization

In the present chapter, the question of whether expressive skills are better predictors than receptive skills of word recognition is discussed. Productive vocabulary skills have been shown to contribute to the developing lexical-semantic system, in Studies I, II, and III, where they were measured. Previous developmental studies (cf. Introduction) exploring word recognition at early stages have demonstrated that productive rather than receptive skills are correlated with the speed and accuracy of word processing (e.g., Fernald, et al., 2001, 2006). Productive skills have also been shown to modulate the amplitudes of language-related ERPs and their scalp distribution, suggesting that enhanced experience with words modulates brain pattern activity (e.g., Mills et al., 1997). Additionally, the second year is marked by a qualitative change in word producing due an accelerated rate in word learning and efficiency in word processing, which in turn modulates brain pattern activity. Moreover, it has been earlier suggested that evaluating comprehension represent few constraints in developmental studies (Tomasello & Mervis, 1994). Parents often express a difficulty in evaluating their child's words comprehension and might under- or overestimate the number of words known in their child's lexicon. When a child recognizes familiar sounds, the parents might interpret this behavior as the understanding of word meanings. This estimation problem tends to diminish over the second year of life, for it becomes easier to detect word understanding with the child's expressions. Thus, it can be assumed that production is a better indication of word processing.

In Study II, all children for whom the vocabulary size was calculated produced fewer than 50 words. The CDI was returned to thirteen out of twenty participants, yielding in fewer than ten participants in each of the vocabulary groups. Therefore, the absence of interaction between the N400 and the expressive skills might be simply due to a lack of statistical power. This hypothesis is more plausible since earlier studies have demonstrated that productive skills and the occurrence of the N400 priming effect are correlated. For instance, the N400 incongruity effect was found at 12-month-olds, but only in infants who produced four or more words (Friedrich & Friederici, 2010). In a longitudinal study, 19-month-olds who displayed an N400 priming effect had larger vocabulary at 30-months while 19-month-olds who had poorer vocabulary skills did not display an early N400 (Friedrich & Friederici, 2006). When trained with novel picture-word pairs association that were violated during the testing phase, 20-month-olds with high productive skills displayed an N400 priming effect whereas children with lower expressive skills did not (Torkildsen et al., 2008). Altogether these studies suggest that the occurrence of the N400 priming effect and productive vocabulary skills are correlated. Nevertheless, a recent study have shown that the N400 priming effect occurred in infants as young as 6-month-olds (Friedrich & Friederici, 2011), whereas the effect was not found in the whole group of 12-month-olds (Friedrich & Friederici, 2010). The authors suggested that the missing N400 effect at 12-month-olds is related to weaker knowledge of words rather than immature brain structures generating the N400. Still, the relation between vocabulary skills and occurrence of the N400 priming effect over the first and second year is not very clear and future studies will enlighten this issue.

In Study III, the productive vocabulary skills of 24-month-olds were found to contribute to the target looking times. The presence of near and distant competitors interferes with word recognition in the low producers group, whereas in the high producers group interference occurred only in the near competitor condition. This result suggests that advanced vocabulary development contributes to a better establishment of semantic similarity distances between concepts. High productive skills allow more refined semantic organization, rendering word recognition less sensitive to interference during word recognition.

7. Conclusion

Altogether, the five studies reported in the present dissertation demonstrate that in the developing lexical-semantic system, words are organized according to taxonomic relationships and integrated into an interconnected system even before children reach their second birthday (18-months). These findings support further the hypothesis that word meanings are semantically related to each other and are not represented independently at 18-months. Automatic activation and controlled processes were shown to underlie semantic processing, but their neural resources might differ. At 24-months of age, the lexicon is organized according to semantic similarity distances between words, reflecting a graded organization.

In bilingual children, words are taxonomically organized in both the dominant and non-dominant languages. Still, semantic processing in each of the languages might be underlined by distinct neural resources. In cross-language processing, words in one language activate their lexical-semantic representations in the other language and vice versa, but the neural representations underlying lexical-semantic processing in dominant and non-dominant languages are not identical.

To date, little is known about the developing lexical-semantic system; thus, the aim of the current thesis was to contribute to better understanding of how and when words are organized and integrated into an interconnected semantic network. It should be noted that in many of the developmental studies, stimuli were selected from adults' norms and results were interpreted according to models based on adults' word recognition. Despite the increasing number of studies exploring the developing lexical-semantic structure and word recognition during language acquisition, no such norms or models exist for the developing population. Thus, a developmental model based on the present and future studies would be more welcomed.

References

Altarriba, J., & Basnight-Brown, D.M. (2007). Methodological considerations in performing semantic and translation-priming experiments across languages. *Behavior Research Methods, 39* (1), 1-18.

Alvarez, R. P., Holcomb, P. J., & Grainger, J. (2003). Accessing word meaning in two languages: An event-related brain potential study of beginning bilinguals. *Brain and Language, 87* (2), 290–304.

Anderson, J.E., & Holcomb, P.J. (1995). Auditory and visual semantic priming using different stimulus onset asynchronies: An event-related brain potential study. *Psychophysiology, 32*, 177-190.

Anglin, J. (1970). *The growth of word meaning*. Cambridge, Mass.: MIT Press.

Anglin, J. (1977). *Word, object, and conceptual development*. New York: Norton.

Ardal, S., Donald, M.W., Meuter, R., Muldrew, S., Luce, M. (1990). Brain responses to semantic incongruity in bilinguals. *Brain and Language, 39* (2), 187-205.

Arias-Trejo, N., & Plunkett, K. (2009). Lexical-semantic priming effects during infancy. Philosophical Transactions of the Royal Society of London. Series B. *Biological Sciences, 364* (1536), 3633–47.

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* (1-2), 63–80.

Arias-Trejo, N., & Plunkett, K. (2013). What's in a link: associative and taxonomic priming effects in the infant lexicon. *Cognition, 128* (2), 214–27. doi:10.1016/j.cognition.2013.03.008.

Assche, E. Van, Duyck, W., Hartsuiker, R. J., & Diependaele, K. (2009). Does Bilingualism Change Cognate Effects in a Sentence Context. *Psychological Science, 20* (8), 923–927.

Baker, C. (2011). *Foundations of bilingual education and bilingualism* (5th edition). Bristol: Multilingual Matters.

Balota, D.A., Black, S.R, & Cheney, M. (1992). Automatic and attentional priming in young and older adults: reevaluation of the two-process model. *Journal of Experimental Psychology: Human Perception and Performance, 18* (2), 485-502.

Barac, R., & Bialystok, E. (2012). Bilingual effects on development: role of language, cultural background, and education. *Child Development, 83*, 413–422.

Barac, R., Bialystok, E., Castro, D.C., & Sanchez, M. (2014). The cognitive development of young dual language learners: a critical review. *Early Childhood Research Quarterly, 29*, 699–714.

Basnight-Brown, D.M., & Altarriba, J. (2007). Differences in semantic and translation priming across languages: the role of language direction and language dominance. *Memory & Cognition, 35* (5), 953-965.

Becker, C. a. (1980). Semantic context effects in visual word recognition: An analysis of semantic strategies. *Memory & Cognition, 8* (6), 493–512.

Becker, C.A. (1976). Allocation of attention during visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 2* (4), 556-566.

Bedore, L.M., Peña, E.D., Summers, C.L., Boerger, K.M., Resendiz, M.D., Greene, K., Bohman, T.M., & Gillam, R.B. (2012). The measure matters: Language dominance profiles across measures in Spanish–English bilingual children. *Bilingualism, 15* (3), 616-629.

Bentin, S., McCarthy, G., & Wood, C.C. 1985. Event-related potentials, lexical decision and semantic priming. *Electroencephalography and Clinical Neurophysiology, 60*, 343-355.

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), 3253–8.

Bergelson, E., & Swingley, D. (2013). Young toddlers' word comprehension is flexible and efficient. *PloS One, 8* (8), e73359.

Bialystok E, Feng X. (2010). Language proficiency and its implications for monolingual and bilingual children. In: A.Y. Durgunoglu, & C. Goldenberg (Eds). *Dual language learners: The development and assessment of oral and written language*, pp. 121–138. New York: Guilford Press.

Bialystok, E. (2001). *Bilingualism in development: Language, literacy, and cognition*. New York: Cambridge University Press.

Bialystok, E., & Craik, F.I.M. (2010). Cognitive and linguistic processing in the bilingual mind. *Current Directions in Psychological Science, 19*, 19-23.

Bialystok, E., & Luk, G. (2012). Receptive vocabulary differences in monolingual and bilingual adults. *Bilingualism: Language and Cognition, 15* (2), 397-401.

Bialystok, E., & Senman, L. (2004). Executive processes in appearance-reality tasks: the role of inhibition of attention and symbolic representation. *Child Development, 75* (2), 562–579.

Bialystok, E., & Viswanathan, M. (2009). Components of executive control with advantages for bilingual children in two cultures. *Cognition, 112*, 494–500.

Bialystok, E., Craik, F.I.M., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in Cognitive Sciences, 16*, 240-250.

Bialystok, E., Luk, G., Peets, K.F., & Yang, S. (2010). Receptive vocabulary differences in monolingual and bilingual children. *Bilingualism: Language and Cognition, 13*, 525-531.

Bijeljac-Babic, R., Serres, J., Höhle, B., & Nazzi, T. (2012). Effect of bilingualism on lexical stress pattern discrimination in French-learning infants. *PloS one, 7* (2), e30843.

Bion, R.A.H., Borovsky, A., & Fernald, A. (2013). Fast mapping, slow learning: disambiguation of novel word–object mappings in relation to vocabulary learning at 18, 24, and 30 months. *Cognition, 126* (1), 39-53. doi:10.1016/j.cognition.2012.08.008.

Blewitt, P., & Toppino, T. C. (1991). The development of taxonomic structure in lexical memory. *Journal of Experimental Child Psychology, 51*, 296–319.

Bloom, L. (1973). *One word at a time: the use of the single-word utterances before syntax*. The Hague: Mouton.

Bloom, P., & Markson, L. (1998). Capacities underlying word learning. *Trends in Cognitive Sciences, 2* (2), 67-73.

Bloom, P. (2001). Précis of how children learn the meanings of words. *Behavioural and Brain Sciences, 24,* 1095-1103.

Bodner, G. E., & Masson, M. E. J. (2001). Prime validity affects masked repetition priming: evidence for an episodic resource account of priming. *Journal of Memory and Language, 45* (4), 616-647.

Bodner, G. E., & Masson, M. E. J. (2003). Beyond spreading activation: An influence of relatedness proportion on masked semantic priming. *Psychonomic Bulletin & Review, 10* (3), 645–652.

Bosch, L., & Sebastián-Gallés, N. (1997). Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. *Cognition, 65* (1), 33-69.

Bosch, L., & Sebastián-Gallés, N. (2001). Evidence of early language discrimination abilities in infants from bilingual environments. *Infancy, 2* (1), 29-49.

Bressler, S.L., & Ding, M. (2006). Event-related potentials. In: *Wiley Encyclopedia of Biomedical Engineering,* Akay M. (Eds), Wiley: Hoboken.

Brown, C.M., & Hagoort, P. (1993). The processing nature of the N400: evidence from masked priming. *Journal of Cognitive Neuroscience, 5* (1), 34-44.

Brown, C.M., Hagoort, P., & Chwilla, D.J. (2000). An event-related brain potential analysis of visual word priming effects. *Brain and Language*, *72,* 158-190.

Burns, T. C., Yoshida, K. A., Hill, K., & Werker, J. F. (2007). The development of phonetic representation in bilingual and monolingual infants. *Applied Psycholinguistics, 28* (3), 455-474.

Byers-Heinlein, K. (2012). Parental language mixing: Its measurement and the relation of mixed input to young bilingual children's vocabulary size. *Bilingualism: Language and Cognition, 16* (1), 32-48.

Byers-Heinlein, K., & Werker, J.F. (2009). Monolingual, bilingual, trilingual: Infants' language experience influences the development of a word learning heuristic. *Developmental Science, 12* (5), 815-823.

Byers-Heinlein, K., & Werker, J.F. (2013). Lexicon structure and the disambiguation of novel words: evidence from bilingual infants. *Cognition, 128* (3), 407-416.

Byers-Heinlein, K., Burns, T.C., & Werker, J.F. (2010). The roots of bilingualism in newborns. *Psychological Science, 1* (21), 343–348.

Carlson, S.M., & Meltzoff, A.N. (2008). Bilingual experience and executive functioning in young children. *Developmental Science, 11* (2), 282-298.

Chwilla, D.J., Brown, C.M., & Hagoort, P. (1995). The N400 as a function of the level of processing. *Psychophysiology, 32*, 274-285.

Clark, E.V. (1973). What's in a word? On the child's acquisition of semantics in his first language. In T.E. Moore (Ed.) *Cognitive development and the acquisition of language*. New York; Academic Press.

Collins, A.M., & Loftus, E.F. (1975). A spreading-activation theory of semantic processing. *Psychological Review, 82*, 407-428.

Conboy, B.T., & Mills, D.L. (2006). Two languages, one developing brain: event-related potentials to words in bilingual toddlers. *Developmental Science, 9*, 1–12.

Cooper, R.M. (1974). The control of eye fixation by the meaning of spoken language: a new methodology for the real-time investigation of speech perception, memory, and language processing. *Cognitive Psychology, 6*, 84–107.

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

Deacon, D., Uhm, T.J., Ritter, W., Hewitt, S., & Dynowska, A. (1999). The lifetime of automatic semantic priming effects may exceed two seconds. *Cognitive Brain Research, 7,* 465-472.

DeBoer, T., Scott, L.S., & Nelson, C.A. (2007). Methods for acquiring and analyzing infant event-related potentials. In: de Haan, M. (Ed.), *Infant EEG and Event-related Potentials*. Psychology Press, London, pp. 5-37.

De Groot, A. (1984). Primed lexical decision: combined effects of the proportion of related prime-target and the stimulus onset asynchrony of the prime and target. *The Quarterly Journal of Experimental Psychology, 36A* (2), 253-280.

De Groot, A.M.B. (1992). Determinants of word translation. *Journal of Experimental Psychology Learning Memory and Cognition, 18*, 1001-1018.

De Groot, A.M.B. (1995). Determinants of bilingual lexicosemantic organisation. *Computer Assisted Language Learning, 8,* 151-180.

De Haan, M. (2013). *Infants EEG and event-related potentials,* de Haan, M. (Ed). Psychology Press. Taylor & Francis Group, Hove & New-York.

De Houwer, A. (2007). Parental language input patterns and children's bilingual use. *Applied Psycholinguistics, 28* (3), 411–424.

De Houwer, A. (2009). *Bilingual first language acquisition*. Bristol, UK: Multilingual Matters.

Delle Luche, C., Durrant, S., Floccia, C., & Plunkett, K. (2014). Implicit meaning in 18-month-old toddlers. *Developmental Science, 17* (6), 948–55.

Den Heyer, K., Briand, K., & Dannenbring, G. L. (1983). Strategic factors in a lexical-decision task: Evidence for automatic and attention-driven processes. *Memory & Cognition, 11* (4), 374–381.

Dijkstra, A. (2005). Bilingual visual word recognition and lexical access. In J.F. Kroll & A. De Groot (Eds.), *Handbook of Bilingualism: Psycholinguistic Approaches* (pp. 178-201). Oxford University Press.

Dijkstra, A., & Van Heuven, W.J.B. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition, 5*, 175-197.

Duñabeitia, J. A., Perea, M., & Carreiras, M. (2010). Masked translation priming effects with highly proficient simultaneous bilinguals. *Experimental Psychology, 57* (2), 98–107.

Duyck, W., Assche, E.V., Drieghe, D., Hartsuiker, R.J. (2007). Visual word recognition by bilinguals in a sentence context: Evidence for nonselective lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33* (4), 663-679.

Elman, J., Bates, E., Johnson, M., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development.* Cambridge, MA: MIT Press.

Federmeier, K.D., & Kutas, M. (1999). A rose by any other name: long-term memory structure and sentence processing. *Journal of Memory and Language, 41*, 469-495.

Fennell, C. T., Byers-Heinlein, K., & Werker, J. F. (2007). Using speech sounds to guide word learning: The case of bilingual infants. *Child development, 78* (5), 1510-1525.

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* (1), 98-116.

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* (3), 228-231.

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

Fernald, A., Zangl, R., Portillo, A.L., & Marchman, V.A. (2008). Looking while listening: using eye movements to monitor spoken language comprehension by infants and young children. In: Sekerina, I.A., Fernandez, E.M., & Clahsen, H. (2008). *Developmental Psycholinguistics: On-line methods in children's language processing,* John Benjamins: Amsterdam, 97-135.

Fischler, I. (1977). Semantic facilitation without association in a lexical decision task. *Memory & Cognition, 5* (3), 335-339.

Foy, J.G., & Mann, V. A. (2013). Bilingual children show advantages in non-verbal auditory executive function task. *International Journal of Bilingualism.*

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*, 1465-1477.

Friedrich, M., & Friederici, A.D. (2005a). Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. *NeuroReport, 16* (6), 653-656.

Friedrich, M., & Friederici, A.D. (2005b). Phonotactic knowledge and lexical-semantic processing in one-year-olds: brain responses to words and nonsense words in picture contexts. *Journal of Cognitive Neuroscience, 17*, 1785-1802.

Friedrich, M., & Friederici, A.D. (2005c). Semantic sentence processing reflected in the event-related potentials of one- and two-year-old children. *NeuroReport, 16* (16), 1801-1804.

Friedrich, M., & Friederici, A.D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43*, 1-12.

Friedrich, M., & Friederici, A.D. (2008). Neurophysiological correlates of online word learning in 14-month-old infants. *NeurReport, 19* (18), 1757-1761.

Friedrich, M., & Friederici, A.D. (2010). Maturing brain mechanisms and developing behavioral language skills. *Brain and Language, 114*, 66-71.

Friedrich, M., & Friedrici, A.D. (2011). Word learning in 6-month-olds: fast encoding-weak retention. *Journal of Cognitive Neuroscience*, 23, 3228-3240.

Ganger, J., & Brent, M.R. (2004). Reexamining the vocabulary spurt. *Developmental Psychology, 40* (4), 621-632.

Garcia-Sierra, A., Rivera-Gaxiola, M., Percaccio, C.R., Conboy, B.T., Romo, H., Klarmin, L., Ortiz, S., & Kuhl, P.K. (2011). Bilingual language learning: an ERP study relating early brain responses to speech, language input, and later word production. *Journal of Phonetics, 39*, 546–557.

Genesee, F. (1989). Early bilingual development: one language or two? *Journal of Child Language, 16* (1), 161-179.

Genesee, F. (2003). Rethinking bilingual acquisition. In J.M. deWaele (Ed.) *Bilingualism: Challenges and directions for future research* (pp. 158-182).Clevedon, UK: Multilingual Matters.

Genesee, F. (2006). Bilingual first language acquisition. In E. McCardle & E. Hoff (Eds.), *Childhood bilingualism: Research on infancy through school age*, (pp. 45–67). Clevedon, UK: Multilingual Matters.

Genesee, F., Boivin, I., & Nicoladis, E. (1996). Talking with strangers: a study of bilingual children's communicative competence. *Applied Psycholinguistics, 17*, 427-442.

Genesee, F., Nicoladis, E., & Paradis, J. (1995). Language differentiation in early bilingual development. *Journal of Child Language, 22*, 611-631.

Gervain, J., & Werker, J.F. (2013). Prosody cues word order in 7-month-old bilingual infants. *Nature Communications, 4*, Article number: 1490.

Geyer, A., Holcomb, P., Midgley, K.J., & Grainger, J. (2011). Processing words in two languages: an event-related brain potential study of proficient bilinguals. *Journal of Neurolinguistics, 24* (3), 338-351.

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

Gollan, T. H., Forster, K. I., & Frost, R. (1997). Translation priming with different scripts: Masked priming with cognates and noncognates in Hebrew-English bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23* (5), 1122–1139.

Grainger J., Midgley K., Holcomb P. J. (2010). Re-thinking the bilingual interactive-activation model from a developmental perspective (BIA-d). In: *Language Acquisition Across Linguistic and Cognitive Systems*, 267–284. M. Kail, & M. Hickmann (Eds). New York: John Benjamins.

Grainger, J. & Dijkstra, T. (1992). On the representation and use of language information in bilinguals. In R. J. Harris (Ed.) *Cognitive processing in bilinguals*. Amsterdam: North Holland.

Grosjean, F. (1998). Studying bilinguals: Methodological and conceptual issues. *Bilingualism: Language and Cognition, 1* (2), 131-149.

Grosjean, F. (2010). Bilingual life and reality. Cambridge, MA: Harvard University Press.

Guasch, M., Sanchez-Casas, R., Ferré, P., & Garcia-Albea, J.E. (2011). Effects of the degree of meaning similarity on cross-language semantic priming in highly proficient bilinguals. *Journal of Cognitive Psychology, 23* (8), 942-961.

Hahne, A. (2001). What's different in second-language processing ? Evidence from event-related brain potentials. *Journal of Psycholinguistic Research, 30* (3), 251–266.

Hahne, A., & Friederici, A.D. (2001). Processing a second language: late learners' comprehension mechanisms as revealed by event-related brain potentials. *Bilingualism: Language and Cognition, 4 (2), 123-141*.

Hashimoto, N., McGregor, K.M., & Graham, A. (2007). Conceptual organization at 6 and 8 years of age: evidence from the semantic priming of object decisions. *Journal of Speech, Language, and Hearing Research, 50* (1), 161-176.

Hernandez, A., Ping, L., & Macwhinney, B. (2005). The emergence of competing modules in bilingualism. *Trends in Cognitive Sciences, 9* (5), 220-225.

Hernandez, A., Li, P., & MacWhinney, B. (2005). The emergence of competing modules in bilingualism. *Trends in Cognitive Sciences, 9*, 220–225.

Hill, H., Strube, M., Roesch-Ely, D., & Weisbrod, M. (2002). Automatic vs. Controlled processes in semantic priming – differentiation by event-related potentials. *International Journal of Psychophysiology, 44*, 197-218.

Hill, H., Ott, F., & Weisbrod, M. (2005). SOA-dependent N400 and P300 semantic priming effects using pseudowords and a delayed lexical decision. *International Journal of Psychophysiology, 56* (3), 209-221.

Holcomb, P.J. (1988). Automatic and attentional processing: an event-related brain potential analysis of semantic priming. *Brain and Language, 35* (1), 66-85.

Holcomb, P.J., & Neville, H.J. (1990). Auditory and visual semantic priming in lexical decision: a comparison using event-related brain potentials. *Language and Cognitive Processes, 5*, 281-312.

Hoshino, N., Midgley, K.J., Holcomb, P.J., & Grainger, J. (2010). An ERP investigation of masked cross-script translation priming. *Brain Research, 1344*, 159-172.

Hoshino, N., & Thierry, G. (2011). Language selection in bilingual word production: electrophysiological evidence for cross-language competition. *Brain Research, 1371,* 100-109.

Huettig, F., & Altmann, G. T. M. (2005). Word meaning and the control of eye fixation: semantic competitor effects and the visual world paradigm. *Cognition, 96* (1), B23–32.

Huettig, F., & Altmann, G.T.M. (2004). The online processing of ambiguous and unambiguous words in context: evidence from head-mounted eye-tracking. In M. Carreiras, & C. Clifton (Eds.), *The online study of sentence comprehension: eye-tracking, ERP and beyond* (pp. 187-207). New-York, NY: Psychology Press, 187-207.

Huettig, F., Rommers, J., & Meyer, A. S. (2011). Using the visual world paradigm to study language processing: a review and critical evaluation. *Acta Psychologica, 137* (2), 151–71. doi:10.1016/j.actpsy.2010.11.003.

Hurtado, N., Marchman, V.A., & Fernald, A. (2008). Does input influence uptake? Links between maternal talk, processing speed and vocabulary size in Spanish-learning children. *Developmental Science, 11* (6), F31-F39.

Hutchison, K.A., Neely, J.H., & Johnson, J.D. (2001). With great expectations, can two "wrongs" prime a "right"? *Journal of Experimental Psychology: Learning, Memory, & Cognition, 6* (27), 1451-1463.

Huttenlocher, J. (1974). The origins of language comprehension. In: *Theories in cognitive psychology: The Loyola Symposium*, R.L. Solso (Ed), Oxford, England: Lawrence Erlbaum, xi, pp. 386.

Inhelder, B., & Piaget, J. (1064). *The early growth of logic in the child.* New-York: Newton.

Isel, F., Baumgaertner, A., Thrän, J., Miesel, J.M., & Büchel, C. (2010). Neural circuitry of the bilingual mental lexicon: effect of age of second language acquisition. *Brain and Cognition, 72* (2), 169-180.

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,* 1672–1682.

Jusczyk, P.W., Cutler, A., & Redanz, N. (1993). Preference for the predominant stress patterns of English words. *Child Development, 64*, 675-687.

Kaan, E., Harris, A., Gibson, E., & Holcomb, P. (2000). The P600 as an index of syntactic integration difficulty. *Language and Cognition Processes, 15* (2), 159–201.

Kovacs, Á. M., & Mehler, J. (2009). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences, 106* (16), 6556–6560.

Kovelman, I., Baker, S.A., Petitto, L.A. (2008). Bilingual and monolingual brains compared: a functional magnetic resonance imaging investigation of syntactic processing and a possible ‘‘neural signature’’ of bilingualism. *Journal of Cognitive Neuroscience, 20,* 153-169.

Kroll, J. F., & De Groot, A. M. B., Eds. (2005). *Handbook of bilingualism: Psycholinguistic approaches*. New York: Oxford University Press.

Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language, 33*, 149-174.

Kroll, J. F., Bobb, S., & Wodniekca, Z. (2006). Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. *Bilingualism: Language and Cognition, 9*, 119-135.

Kroll, J. F., Van Hell, J. G., Tokowicz, N., & Green, D. W. (2010). The Revised Hierarchical Model: A critical review and assessment. *Bilingualism: Language and Cognition*, *13,* 373-381.

Kuipers, J. R., & Thierry, G. (2013). ERP-pupil size correlations reveal how bilingualism enhances cognitive flexibility. *Cortex, 49* (10), 2853-2860.

Kutas, M., & Federmeier, K.D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences, 4* (12), 463-470.

Kutas, M., Van Petten, C., & Besson, M. (1988). Event-related potential asymmetries during the reading of sentences. *Electroencephalography and clinical Neurophysiology, 69,* 218-233.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62,* 621–47.

Kutas, M., & Hillyard, S.A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207,* 203-205.

Lieven, E. (2011). Bilingual language acquisition. *Human Development, 53* (5), 256-263.

Lin, E. L., & Murphy, G.L. (2001). Thematic relations in adults' concepts. *Journal of Experimental Psychology: General, 130,* 3-28.

McCarthy, G., & Wood, C.C. (1985)/ Scalp distributions of event-related potentials: an ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62* (3), 203-208.

Marchman VA, Fernald A, Hurtado N. (2009). How vocabulary size in two languages relates to efficiency in spoken word recognition by young Spanish-English bilinguals. *Journal of Child Language, 37,* 817–840.

Marian, V., & Spivey, M. (2003). Competing activation in bilingual language processing: Within- and between-language competition. *Bilingualism: Language and Cognition, 6* (2), 97–115.

Martin-Rhee, M., & Bialystok, E. (2008). The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism: Language and Cognition, 11* (1), 81–93.

Masson, M.E.J. (1991). A distributed memory model of context effects in word identification. In D. Besner & G.W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 233-263). Hillsdale, NJ: Erlbaum.

Masson, M.E.J. (1995). A distributed memory model of semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21* (1), 3-23.

McCauley, C., Weil, C., & Sperber, R. D. T. (1976). The development of memory structure as reflected by semantic-priming effects. *Journal of Experimental Child Psychology, 22*, 511–518.

McRae, K., & Boisvert, S. (1998). Automatic semantic similarity priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24* (3), 558-572.

Meyer, D., & Schvaneveldt, R. (1971). Facilitation in recognizing pairs of words: evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90* (2), 227–234.

Midgley, K.J., Holcomb, P.J., & Grainger, J. (2009). Masked repetition and translation priming in second language learners: a window on the time-course of form and meaning activation using ERPs. *Psychophysiology, 46* (3), 551–565.

Mills, D.L., Coffey-Corina, S.A., & Neville, H. (1993). Language acquisition and cerebral specialization in 20-month-old infants. *Journal of Cognitive Neuroscience, 5* (3), 317-334.

Mills, D.L., Coffey-Corina, S., Neville, H.J. (1997). Language comprehension and cerebral specialization from 13 to 20 months. *Developmental Neuropsychology, 13* (3), 397-445.

Mills, D.L., Plunkett, K., Prat, C., & Schafer, G. (2005). Watching the infant brain learn words: effect of vocabulary size and experience. *Cognitive Development, 20* (1), 19-31.

Mirman, D., & Magnuson, J. S. (2008). Attractor dynamics and semantic neighborhood density: processing is slowed by near neighbors and speeded by distant neighbors. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 34*, 65-79.

Mirman, D., & Magnuson, J. S. (2009). Dynamics of activation of semantically similar concepts during spoken words recognition. *Memory & Cognition, 37* (7), 1026-1039.

Morales, J., Calvo, A., & Bialystok, E. (2013). Working memory development in monolingual and bilingual children. *Journal of Experimental Child Psychology, 114* (2), 187–202.

Moreno, E. M., & Kutas, M. (2005). Processing semantic anomalies in two languages: an electrophysiological exploration in both languages of Spanish-English bilinguals. *Brain Research. Cognitive Brain Research, 22* (2), 205–20.

Moreno, E.M., Rodriguez-Fornells, A., & Laine, M. (2008). Event-related potentials (ERPs) in the study of bilingual language processing. *Journal of Neurolinguistics, 21* (6), 477-508.

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology, 118* (12), 2544-2590.

Nazzi, T., & Bertoncini, J. (2003). Before and after the vocabulary spurt: two modes of word acquisition? *Developmental Science, 6* (2), 136–142.

Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General, 106* (3), 226–254.

Neely, J.H. (1991). Semantic priming effects in visual word recognition: a selective review of current findings and theories. In: Besner, D., Humphreys, G.W. (Eds), Basic progress in Reading – Visual Word Recognition. Erlbaum, Hillsdale, NJ, pp. 264-333.

Neely, J.H., & Keefe, D.E. (1989). Semantic context effects on visual word processing: a hybrid prospective-retrospective processing theory. In G.H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory*, pp. 207-248. New York: Academic.

Neely, J.H., Keefe, D.E., & Ross, K.L. (1989). Semantic priming in the lexical decision rask: roles of prospective prime-generated expectancies and retrospective semantic matching. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 1003-1019.

Nieuwenhuis, S., Aston-Jones, G., & Cohen, J.D. (2005). Decision making, the P3, and the locus coeruleus-norepinephrine system. *Psychological Bulletin*, *131 (*4), 510-532.

Nelson, K. (1985). *Making sense: the acquisition of shared meaning.* New-York. Academic Press.

Nelson, D.G.K., Jusczyk, P.W., Mandel, D.R., Myers, J., Turk, A., & Gerken, L.A. (1995). The head-turn preference procedure for testing auditory perception. *Infant Behavior and Development, 18,* 111-116.

Ojima, S., Nakamura, N., Matsuba-Kurita, H., Hoshino, T., & Hagiwara, H. (2011). Neural correlates of foreign-language learning in childhood: A 3-year longitudinal ERP study. *Journal of Cognitive Neuroscience*, *23* (1), 183-199.

Okanda, M., Moriguchi,Y., & Itakura, S. (2010). Language and cognitive shifting: evidence from young monolingual and bilingual children. *Psychological Reports, 107* (1), 68–78.

Oller, D., Eilers, R. E., Urbano, R., & Cobo-Lewis, A. B. (1997). Development of precursors to speech in infants exposed to two languages. *Journal of child language, 24* (02), 407-425.

Oller, D.K., B.Z., Pearson, & Cobo-Lewis, A.B. (2007). Profile effects in early bilingual language and literacy. *Applied Psycholinguistics, 28* (2): 191–230.

Osterhout, L., McLaughlin, J., & Bersick, M. (1997). Event-related brain potentials and human language. *Trend in Cognitive Sciences, 1* (6), 203-209.

Parise, E., & Csibra, G. (2012). Electrophysiological evidence for the understanding of maternal speech by 9-month-old infants. *Psychological Science, 23* (7), 728-733.

Patterson, J. L. & Pearson, B. Z. (2004). Bilingual lexical development: Influences, contexts, and processes. In B. A. Goldstein (Ed.), *Bilingual language development and disorders in Spanish-English speakers* (pp. 77-104). Baltimore, MD: Paul H. Brookes.

Pearson, B. Z., Fernandez, S. C., & Oller, D. K. (1993). Lexical development in bilingual infants and toddlers: Comparison to monolingual norms. *Language learning, 43* (1), 93-120.

Pearson, B.Z., Fernandez, S.C., Lewedeg, V., & Oller, D.K. (1997). The relation of input factors to lexical learning by bilingual infants. *Applied Psycholinguistics, 18* (1), 41-58.

Perea, M., & Rosa, E. (2002). The effects of associative and semantic priming in the lexical decision task. *Psychological Research, 66* (3), 180–94.

Petitto, L. A., Katerelos, M., Levy, B. G., Gauna, K., Tétreault, K., & Ferraro, V. (2001). Bilingual signed and spoken language acquisition from birth: Implications for the mechanisms underlying early bilingual language acquisition. *Journal of child language, 28* (2), 453-496.

Pierce, L.J., Klein, D., Chen, J.K., Delcenserie, A., & Genesee, F. (2014). Mapping the unconscious maintenance of a lost first language. *Proceedings of the National Academy of Sciences of the United States of America, 111* (48), 17314-17319.

Polka, L., & Sundara, M. (2003). Word segmentation in monolingual and bilingual infant learners of English and French. In *Proceedings of the 15th International Congress of Phonetic Sciences*, pp. 1021–1024.

Posner, M.I., Snyder, C.R.R. (1975). Attention and Cognitive control. In: Solso, R.L. (Ed.), *Information Progressing and Cognition: The Loyota Symposium*. Erlbaum, Hillsdale, NJ, pp. 55-85.

Poulin-Dubois, D., Bialystok, E., Blaye, A., Polonia, A., & Yott, J. (2013). Lexical access and vocabulary development in very young bilinguals. *International Journal of Bilingualism, 17* (1), 57-70.

Poulin-Dubois, D., Frank, I., Graham, S.A., & Elkin, A. (1999). The role of shape similarity in toddlers' lexical extensions. *British Journal of Developmental Psychology, 17,* 21-36.

Quillian, M.R. (1962). A revised design for an understanding machine. *Mechanical Translation, 7,* 17-29.

Ratcliff, R., & McKoon, G. (1988). A retrieval theory of priming in memory. *Psychological Review, 95* (3), 385-408.

Rescorla, L.A. (1980). Overextension in early language development. *Journal of Child Language*, 7, 321-335.

Reznick, J.S. (1990). Visual preference as a test of infant word comprehension. *Applied Psycholinguistics, 11*, 145-166.

Ritchie, W.C., & Bhatia, T.K. (2012). Social and psychological factors in language mixing. In: *The Handbook of Bilingualism and Multilingualism, Second Edition*. Edited by T.K. Bahtia & W.L. Ritchie. Wiley-Blackwell.

Sanchez-casas, R., Ferré, P., Garcia-Albea, J., & Guasch, M. (2006). The nature of semantic priming: effects of the degree of semantic similarity between primes and targets in Spanish. *European Journal of Cognitive Psychology, 18* (2), 161-184.

Schoonbaert, S., Duyck, W., Brysbaert, M., & Hartsuiker, R. J. (2009). Semantic and translation priming from a first language to a second and back: Making sense of the findings. Memory & *Cognition, 37* (5), 569–86.

Schoonbaert, S., Holcomb, P., Grainger, J., & Hartsuiker, R.J. (2011). Testing asymmetries in noncognate translation priming: evidence from RTs and ERPs. *Psychophysiology, 48* (1), 74–81.

Schvaneveldt, R., Ackerman, B. P., & Semlear, T. (1977). The effect of semantic context on children's word recognition. *Child Development, 48*, 612–616.

Sebastian-Galles, N., Albareda-Castellot, B., Weikum, W.M., & Werker, J.F. (2012). A bilingual advantage in visual language discrimination. *Psychological Science, 23* (9), 994-999.

Seidenberg, M.S., Waters, G.S., Sanders, M., & Langer, P. (1984). Pre- and postlexical loci of contextual effects on word recognition. *Memory & Cognition, 12* (4), 315-328.

Seliger, H.W. (1982). On the possible role of the right hemisphere in second language acquisition. *Tesol Quarterly, 16* (3), 307-315.

Shelton, J.R., & Martin, R.C. (1992). How semantic is automatic semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18* (6), 1191-1210.

Shiffrin, R.M., & Schneider, W. (1977). Controlled and automatic human information processing: perceptual learning, automatic attending, & a general theory. *Psychological Review, 84* (2), 127-190.

Silva-Pereyra, J., Harmony, T., Villanueva, G., Fernandez, T., Rodriguez, M., Galan, L., Diaz-Comas, L., Bernal, J., Fernandez-Bouzas, A., Marosi, E., Reyes, A. (1999). N400 and lexical decisions: automatic or controlled processing? *Clinical Neurophysiology, 110,* 813-824.

Silva Pereyra, J.F., Klarman, L., Lin, L. J-F., & Kuhl, P.K. (2005). Sentence processing in 30-month-old children: an event-related potential study. *Neuroreport*, *16* (6), 645-648.

Silverberg, R., Bentin, S., Gaziel, T., Obler, L.K., & Albert, M.L. (1979). Shift of visual fiel preference for English words in native Hebrew speakers. *Brain and Language, 8* (2), 184-190.

Silverberg, S., & Samuel, A. G. (2004). The effect of age of second language acquisition on the representation and processing of second language words. *Journal of Memory and Language, 51* (3), 381–398.

Singh, L. (2014). One World, Two Languages: Cross-Language Semantic Priming in Bilingual Toddlers. *Child development, 85* (2), 755-766.

Smith, E.E., Shoben, E.J., & Rips, L. (1974). Structure and process in semantic memory: a featural model for semantic decisions. *Psychological Review, 81* (3), 214-241.

Spivey, M. & Marian, V. (1999). Cross talk between native and second languages: partial activation of an irrelevant lexicon. *Psychological Science, 10*, 281–284.

Stolz, J. A., & Neely, J. H. (1995). When target degradationdoes and does not enhance semantic context effects inword recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*,596–611.

Styles, S. J., Arias-Trejo, N., & Plunkett, K. (2008). Priming and lexical interference in infancy. In *Proceedings of the annual meeting of the cognitive science society*, Washington, DC.

Styles, S. J., & Plunkett, K. (2009). How do infants build a semantic system? Language and *Cognition, 1* (01), 1–24.

Swingley, D., & Fernald, A. (2002). Recognition of Words Referring to Present and Absent Objects by 24-Month-Olds. *Journal of Memory and Language, 46* (1), 39–56.

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

Thierry, G. (2005). The Use of Event-Related Potentials in the Study of Early Cognitive Development. *Infants and Child Development, 14* (1), 85-94.

Thierry, G., Vihman, M., & Roberts, M. (2003). Familiar words capture the attention of 11-month-olds in less than 250 ms. *NeuroReport, 14* (8), 2307-2310.

Thierry, G., & Wu, Y. J. (2007). Brain potentials reveal unconscious translation during foreign-language comprehension. *Proceedings of the National Academy of Sciences of the United States of America, 104* (30), 12530–5.

Thomson, J.R., & Chapman, R.S. (1977). Who is 'Daddy' revisited: the status of two-year-olds' over-extended words in use and comprehension. *Journal of Child Language, 4* (3), 359-375.

Torkildsen, J. vK., Sannerud, T., Syversen, G., Thormodsen, R., Simonsen, H.G., Moen, I., Smith, L., et Lindgren, M. (2006). Semantic organization of basic-level words in 20-month-olds: An ERP study. *Journal of Neurolinguistics, 19*, 431-454.

Torkildsen, J.K., Svangstu, J.M., Hansen, H.F., Smith, L., Simonsen, H.G., Moen, I., & Lindgren, M. (2008). Productive vocabulary size predicts event-related potential correlates of fast mapping in 20-month-olds. *Journal of Cognitive Neuroscience, 20* (7), 1266-1282.

Torkildsen, J. von Koss, 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.

Tweedy, J. R., Lapinski, R. H., & Schvaneveldt, R. W. (1977). Semantic-context effects on word recognition: Influence of varying the proportion of items presented in an appropriate context. *Memory & Cognition, 5* (1), 84–9.

Van Hell, J.G., & de Groot, A.M.B. (1998). Conceptual representation in bilingual memory: Effects of concreteness and cognate status in word association. *Bilingualism: Language and Cognition, 1* (3), 193-211.

Van Heuven, W.J.B., Dijkstra, T. & Grainger, J. (1998). Orthographic Neighborhood Effects in Bilingual Word Recognition. *Journal of Memory and Language, 39*, 458-483.

Van Petten, C., & Luka, B.J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and Language, 97*, 279-293.

Ventureyra, V. a. ., Pallier, C., & Yoo, H.-Y. (2004). The loss of first language phonetic perception in adopted Koreans. *Journal of Neurolinguistics*, *17* (1), 79–91.

Vigliocco, G., Vinson, D. P., Lewis, W., & Garrett, M. F. (2004). Representing the meanings of object and action words: the featural and unitary semantic space hypothesis. *Cognitive Psychology*, *48* (4), 422–88.

Vihman, M. M., Thierry, G., Lum, J., Keren-Portnoy, T., & Martin, P. (2007). Onset of word form recognition in English, Welsh, and English-Welsh bilingual infants. *Applied Psycholinguistics*, *28* (3), 475.

Voga, M., & Grainger, J. (2007). Cognate status and cross-script translation priming. *Memory & Cognition, 35* (5), 938-952.

Volterra, V. & Taeschner, T. (1978). The acquisition and development of language by bilingual children. *Journal of Child Language, 5,* 311-326.

Von Holzen, K., & Mani, N. (2012). Language nonselective lexical access in bilingual toddlers. *Journal of Experimental Child Psychology, 113,* 569-586.

Waxman, S.R., Namy, L.L. (1997). Challenging the notion of a thematic preference in young children. *Developmental Psychology*, *33*, 555–567.

Weber-Fox, C.M., & Neville, H. J. (1996). Maturational constraints on functional specialization for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience, 8* (3), 231-256.

Weikum, W.M., Vouloumanos, A., Navarra, J., Soto-Faraco, S., Sebastian-Gallés, N., & Werker, J.F. (2007). Visual language discrimination in infancy. *Science, 316* (5828), 1159.

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 : The Official Journal of the International Society on Infant Studies, 18* (6), 1–23.

Wu, Y.J., & Thierry, G. (2010). Chinese-English bilinguals reading English hear Chinese. *The Journal of Neuroscience, 30* (22), 7646-7651.

Yamamoto, M. (2001). Language use in interlingual families: A Japanese–English sociolinguistic study. Clevedon: Multilingual Matters.

Yang, S., Yang, H.,& Lust, B. (2011). Early childhood bilingualism leads to advances in executive attention: dissociating culture and language. *Bilingualism: Language and Cognition, 14* (3), 412-422.

Yee, E., & Sedivy, J. C. (2006). Eye movements to pictures reveal transient semantic activation during spoken word recognition. Journal of Experimental Psychology. *Learning, Memory, and Cognition, 32* (1), 1–14.

Yee, E., Overton, E., & Thompson-Schill, S.L. (2009). Looking for meaning: eye-movements are sensitive to overlapping semantic features, not association. *Psychonomic Bulletin & Review, 16* (5), 869-874.

Zangl, R., Klarman, L., Thal, D., & Bates, E. (2001). On-line word processing in infants and toddlers: the role of age, vocabulary and perceptual degradation. *Technical Report: Project in Cognitive and Neural Development Center for Research in Language*. University of California, San Diego. La Jolla, CA 92093-0526.

Zangl, R., Klarman, L., Thal, D., Fernald, A., & Bates, E. (2005). Dynamics of word comprehension in infancy: developments in timing, accuracy, and resistance to acoustic degradation. *Journal of Cognition and Development, 6* (2), 179-208.