

Getting it right: Word learning across the hemispheres

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ABSTRACT

The brain is able to acquire information about an unknown word's meaning from a highly constraining sentence context with minimal exposure. In this study, we investigate the potential contributions of the cerebral hemispheres to this ability. Undergraduates first read weakly or strongly constraining sentences completed by known or unknown (novel) words. Subsequently, their knowledge of the previously exposed words was assessed via a lexical decision task in which each word served as visual primes for lateralized target words that varied in their semantic relationship to the primes (unrelated, identical or synonymous). As expected, smaller N400 amplitudes were seen for target words preceded by identical (vs. unrelated) known word primes, regardless of visual field of presentation. When Unknown words served as primes, N400 reductions to synonymous target words were observed only if the prime had appeared under High sentential constraint; targets appearing in the LVF/RH elicited a small N400 effect and modulation of a subsequent late positivity whereas those in the RVF/LH elicited modulation on the late positivity only. Unknown words initially seen in Low constraint contexts showed priming effects only in a late positivity and only in the RVF/LH. Strength of contextual constraint clearly seems to impact the hemispheres' rapid acquisition of novel word meanings. N400 modulation for novel words under strong contextual constraint in the LVH/RH suggests that fast-mapped lexical representations may initially activate meanings that are weakly, distantly, associatively or thematically-related. More extensive and bilateral semantic processing seems to occur at longer processing latencies (post N400).

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1. Introduction

There is now abundant evidence that both cerebral hemispheres participate in all manner of linguistic tasks, albeit differently (see Federmeier, Wlotko, & Meyer, 2008 for a review). For example, cerebral asymmetries in word knowledge have been extensively documented over the past several decades (e.g. Bouaffre & Faita-Ainseba, 2007; Burgess & Simpson, 1988; Chiarello, Burgess, Richards, & Pollock, 1990; Grose-Fifer & Deacon, 2004; Koivisto & Laine, 2000). This body of work has repeatedly revealed that both sides of the brain represent and activate non-identical aspects of known word meanings. In contrast, there has been nearly no investigation of how of novel word representations develop across the hemispheres. The major goal of this study is to address this question by exploring the potential contributions of the cerebral hemispheres to the initial representation(s) of fast-mapped word meanings.

How humans understand and represent new word meanings is most commonly investigated in young children even though the majority of our vocabulary is acquired after early childhood and throughout adulthood (Anglin, 1993; Sternberg, 1987). Learners of all ages are able to infer a word's meaning rapidly, sometimes after only a single exposure in certain contexts (a process known as fast-mapping; Carey & Bartlett, 1978; Dollaghan, 1985; Heibeck & Markman, 1987) such as when a word's meaning is strongly constrained. This rapidly acquired knowledge about word meaning is manifold, and can include awareness of its appropriate usage in a sentence and its semantic relationship to other words. However, this initially stored representation is likely to be fragile, and may change significantly with further exposure or consolidation (Dumay & Gaskell, 2007; Gaskell & Dumay, 2003). Both processes are fundamental to word learning: fast-mapping lays the foundation for future learning, while slow-mapping involves reanalysis, integration and consolidation of word meaning. In this study, we focus specifically on the hemispheric contributions to fast-mapped representations.

Older children and adult Learners may frequently encounter novel words through reading (Jenkins, Stein, & Wysocki, 1984; Nagy, Anderson, & Herman, 1987; Nagy, Herman, & Anderson, 1985;

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Sternberg, 1987), thereby requiring them to swiftly (and often implicitly) infer the meaning, appropriate usage, and semantic relationships of a word using contextual cues alone. A primary goal of this study is to examine potential hemispheric contributions to the novel word representation(s) that results from this contextual mode of fast-mapping in young adults.

To date, our understanding of initially acquired neural representations of lexical meanings has been derived from studies that probe joint or coordinated contributions from both cerebral hemispheres. This foundational work has documented that electrical brain activity can rapidly reflect acquisition of word meanings over periods ranging from a single trial to several weeks (Batterink & Neville, 2011; Borovsky, Elman, & Kutas, 2012; Borovsky, Kutas, & Elman, 2010; Friedrich & Friederici, 2008; McLaughlin, Osterhout, & Kim, 2004; Mestres-Misse, Rodriguez-Fornells, & Munte, 2007; Ojima, Nakata, & Kakigi, 2005; Perfetti, Wlotko, & Hart, 2005; Rodriguez-Fornells, Cunillera, Mestres-Misse, & de Diego-Balaguer, 2009; Stein et al., 2006; Torkildsen et al., 2008). In cases where word meanings have been acquired after only a single exposure, the strength of the contextual constraint is a critical determinant in its initial representation. Prior studies have found that strongly but not weakly constraining contexts support knowledge of appropriate usages of a word as the object of a verb, as well as an understanding of semantically-related words (Borovsky et al., 2012, 2010; Frishkoff, Perfetti, & Collins-Thompson, 2010).

A number of neuroimaging studies have examined the neuro-anatomical structures involved in word learning (e.g. Breitenstein et al., 2005; Grönholm, Rinne, Vorobyev, & Laine, 2005; Mestres-Missé, Càmara, Rodriguez-Fornells, Rotte, & Münte, 2008; Paulesu et al., 2009; Shtyrov, 2012; Shtyrov, Nikulin, & Pulvermüller, 2010; Ye, Mestres-Missé, Rodriguez-Fornells, & Münte, 2010). This research has identified a network of regions in the left and right hemisphere (though primarily left-lateralized) associated with learning the sound and meaning of novel words. These include the hippocampus, thalamus, inferior frontal gyrus, posterior middle temporal gyrus, cerebellum, among others. Additional proposals suggest that the left hippocampus may be particularly important in the initial encoding and acquisition of word meanings (Davis & Gaskell, 2009; McClelland, McNaughton, & O'Reilly, 1995), while cortical regions are critical for further consolidation of word meanings. However, to our knowledge, no neuroimaging study has yet measured neural changes associated with fast-mapping a word's meaning after only a single exposure in context.

One prototypical way in which the individual contributions of the hemispheres can be assessed in the representation of word meaning is using a divided visual field paradigm (DVF; see Federmeier et al., 2008 for a review). This method involves randomly flashing stimuli to the right or left visual field (RVF or LVF) as a participant fixates on a central point. Lateralized presentation takes advantage of the wiring of the human visual system, which initially sends the majority of information from each visual field to the contralateral hemisphere. This brief headstart in processing is small (10 ms or so), but has been found to have prolonged consequences in behavioral and electrophysiological measurements. It is thus possible to gauge hemisphere-specific asymmetries in lexical processing via the DVF paradigm. Of course, since language function normally depends on rapid and complex inter-hemispheric communication, the function measured from each hemisphere separately in this way does not mean that central vision effects can necessarily be predicted from a simple sum of the activity of the two hemispheres (Federmeier, Mai, & Kutas, 2005). In fact, behavioral and electrophysiological responses to stimuli presented in the DVF technique can differ from centralized presentation in a number of ways. Depending

on the task, responses to stimuli presented in central vision can be largely driven by the LH (e.g. Federmeier & Kutas, 1999a) or RH (e.g. Coulson & Williams, 2005), be identical in both hemispheres (e.g. Coulson, Federmeier, Van Petten, & Kutas, 2005) or be dissimilar to central presentation in both hemispheres (e.g. Wlotko & Federmeier, 2007).

As mentioned above, hemispheric representations of word meaning have been studied via time-locked electrical responses to stimuli of interest, known as event-related brain potentials (ERPs). A specific ERP component, the N400, has been particularly useful for this purpose. The N400 is a negative going potential with a centroparietal maximum peaking approximately 400 ms after the onset of any potentially meaningful stimulus (Kutas & Federmeier, 2001; Kutas & Hillyard, 1980). The N400 response has been extensively studied (Kutas & Federmeier, 2011); its amplitude varies depending on the context in which a word appears, and processing of word meaning. For example, N400 amplitudes are smaller for high frequency words compared to less frequent words (Van Petten & Kutas, 1990), for words that appear in strongly (vs. weakly) expected contexts and thus vary in their expectancy as measured in offline cloze probability (Kutas & Hillyard, 1984), or for words that are preceded by semantically related or identical (vs. unrelated words; Anderson & Holcomb, 1995; Bentin, McCarthy, & Wood, 1985; Brown & Hagoort, 1993; Deacon, Hewitt, Yang, & Nagata, 2000; Nobre & McCarthy, 1994; Ruz, Madrid, Lupianez, & Tudela, 2003). The N400 is also large for pronounceable (pseudo)words whose meaning is unknown or nonexistent (Bentin, 1987; Bentin et al., 1985). Thus N400 amplitudes range from very small when a word is easily understood and integrated into the surrounding context to very large when a (pronounceable) (pseudo)word is unexpected/incongruent or its meaning is unknown.

In addition to the N400, the late-positive component (LPC) is often elicited in conjunction with the N400. The LPC is shown as a late parietal positivity, usually largest between 500 and 900 ms. While the factors that modulate this component are still being determined, it seems to reliably indicate strategic or controlled information retrieval processing during semantic tasks (Olichney et al., 2000; Rugg & Curran, 2007; Van Petten, Kutas, Kluender, Mitchiner, & Mclsaac, 1991), or potentially conscious recognition of prime-target relationships (Duzel, Yonelinas, Mangun, Heinze, & Tulving, 1997). The LPC is thus very large (positive) in cases where meaning relationships may be consciously recognized.

Recently, acquisition of novel word meaning by adults learning words in their first (L1) and second (L2) language has been indexed by electrophysiological components like the N400 (Batterink & Neville, 2011; Borovsky et al., 2010; McLaughlin et al., 2004; Mestres-Misse et al., 2007; Ojima et al., 2005; Perfetti et al., 2005; Stein et al., 2006). These reports detail rapid changes in evoked electrical brain activity to novel words over the course of several weeks of L2 instruction (McLaughlin et al., 2004), over several trials, over the course of a few minutes in L1 (Batterink & Neville, 2011; Mestres-Misse et al., 2007; Perfetti et al., 2005), and even following a single exposure (Borovsky et al., 2012, 2010). Additionally, this work has indicated that the N400 is sensitive to the representation of various dimensions of novel word meanings, including its appropriate usage and semantic relationship to other known words (Batterink & Neville, 2011; Borovsky et al., 2012, 2010; Mestres-Misse et al., 2007; Perfetti et al., 2005).

The semantic organization of lexical knowledge has been examined with both behavioral and electrophysiological measures in the context of the well-studied semantic priming effect (Meyer, 1970). The priming effect is reflected in faster reaction times (RT) (for a review, see Neely, 1991) and/or smaller N400 amplitudes (Anderson & Holcomb, 1995; Bentin et al., 1985; Brown & Hagoort, 1993; Deacon et al., 2000; Nobre & McCarthy,

1994; Ruz et al., 2003) in response to target words preceded by an identical or related word (e.g. doctor–NURSE or doctor–DOCTOR) relative to target words that have been primed by unrelated words or are pseudowords, (e.g. doctor–CHAIR, or doctor–FOOP). Such effects have been generally taken to reflect the functional semantic organization of words in the mental lexicon (Collins & Loftus, 1975; Hutchison, 2003; Lucas, 2000; McRae, deSa, & Seidenberg, 1997; Plaut & Booth, 2000).

Accordingly, we have taken ERP (N400 and subsequent positivity) modulations during semantic priming tasks with novel words as primes as an index of lexical acquisition and representation, reflecting the extent to which a novel word's meaning has been integrated into an individual's mental dictionary. Relying on this logic, researchers have observed that known target words that are semantically related or synonyms of novel word primes (whose meaning has been acquired to some extent) elicit smaller N400 amplitudes than do known target words that are unrelated to the novel word primes (Borovsky et al., 2012; McLaughlin et al., 2004; Mestres-Misse et al., 2007). These findings suggest that relationships between the meanings of known words and novel words are represented in the brain relatively quickly and that this information is evident in at least one electrophysiological index of semantic knowledge—the N400 component. Despite the growing evidence that the N400 is sensitive to lexical representations established after only minimal exposure, prior work has little to say about what each hemisphere contributes to fast-mapped meaning representation—the major goal of our study.

Prior neuropsychological and electrophysiological investigations of lexical acquisition in children points to some potential differences in the relative involvement of the hemispheres in early word representation. ERP studies of infants between 13 and 20 months by Mills and colleagues (Mills, Coffey-Corina, & Neville, 1993; Mills, Coffey-Corina, & Neville, 1997; Mills, Plunkett, Prat, & Schafer, 2005) have indicated a right-to-left shift in the distribution of electrophysiological responses to known words with increasing age and vocabulary. Travis et al. (2011) found that both infants and adults share a similar left-lateralized network that is responsive to words based on anatomically constrained MEG measurements, although infants showed more extensive activation in the RH compared to adults. Acquired brain lesion data also point to the importance of the integrity of both the RH and LH in early vocabulary development (Eisele & Aram, 1993; Thal et al., 1991).

There is, however, nearly no research that examines hemispheric contributions to the establishment of novel lexical representations in adults. The only published study with adults (that we know of) that explicitly probes hemispheric asymmetries in early lexical representation also implicated a potentially important role of the RH for low familiarity, so-called “frontier” words (Ince & Christman, 2002). Taken together, the evidence from adults and children suggests that both hemispheres may make important but different contributions in establishing the initial representation of word meanings; the RH may be more involved in the earliest stages, shifting to the LH with greater familiarity and/or understanding. However, it should be noted that this prior work is only suggestive, and has not directly addressed hemispheric contributions to the representation of fast-mapped word meanings.

Of additional relevance to the present investigation is a substantial compendium of research that examines hemispheric representations to highly familiar word meanings. This work has firmly established that both hemispheres represent non-identical aspects of well-known word meanings and relationships between words/concepts (for reviews, see Beeman & Chiarello, 1998; Federmeier et al., 2008). In general, various proposals regarding hemispheric asymmetries in semantic representation of word meanings seem to ascribe less precise, less selective and slower

speeds of lexical access, activation, and representation to the RH than the LH. Specifically, these hemispheric differences in semantic representation have been characterized as “coarse,” “diffuse,” or “distributed” in the RH and “focused,” “fine,” or “localized” in the LH (Beeman, Friedman, Grafman, & Perez, 1994; Chiarello, 1998; Grose-Fifer & Deacon, 2004). These theories are largely framed and buttressed by findings from semantic priming studies using the DVF technique. For example, studies using this technique have reported stronger priming effects in the RH vs. LH to words primed by distantly related meanings, such as: unassociated category members (Bouaffre & Faita-Ainseba, 2007; Chiarello et al., 1990; Chiarello & Richards, 1992; Deacon et al., 2004; Grose-Fifer & Deacon, 2004; Koivisto, 1997, but cf. Abernethy & Coney, 1996), indirect semantic relations (Kiefer, Weisbrod, Kern, Maier, & Spitzer, 1998), summation primes (Beeman et al., 1994), and subordinate senses of lexically ambiguous word meanings (Burgess & Simpson, 1988). It is thus clear that the hemispheres represent word meanings differently, though the precise nature of the mechanisms underlying these differences are still debated. Nevertheless, there appears to be some agreement that the RH seems to prime more distantly related concepts whereas the LH is more selective in its activation and representation of semantic relationships between words.

These cerebral asymmetries in semantic representation suggest that the LH and RH may participate differently in initial lexical mappings, depending on the breadth or specificity of knowledge that is initially acquired. For example, certain theories of children's early language acquisition propose that early learning is item-based and lexically-specific, with words initially represented and used in a restricted matter, largely imitative of the initial context in which the word was acquired and only later becoming more general and abstract (Lieven, Pine, & Baldwin, 1997; Tomasello, 1992). The punctate and lexically-specific nature of these initially acquired word forms suggests that they may only initially link to and activate closely related concepts or items, leading to a potentially greater role of the LH in early acquisition. An alternate view that we take to be consistent Ince and Christman's proposal (2002; reviewed above) is that the lexical representation of fast-mapped words may not be highly detailed, and thus rely on the RH for initial incorporation into the mental lexicon. Specifically, Ince and Christman (2002) suggest that the RH initially acquires “thematic” relationships between word meanings built from an understanding of the associated words or events appearing in conjunction with a new word (e.g. tailor–suit; bee–honey). Subsequently, they propose that additional experience with a word allows the LH to encode finer-grained categorical aspects of meaning such as the semantic features of a word (cat–furry), category coordinates (dog–goat) or exemplars (robin–bird).

Critically for the present experiment, these hypotheses of novel word representation are derived from extant research that has primarily examined the representation of well-known and highly familiar word meanings. These “slow-mapped” representations are likely to differ in many ways from the initial fast-mapping of a word (Carey & Bartlett, 1978). We believe that in order to gain a full understanding of hemispheric contributions to lexical representation(s) it will be necessary to investigate words not only at their endpoint of knowledge, but throughout the full spectrum of its understanding—including those in their initially-acquired, fast-mapped state. We chose to examine this issue in a task in which learners initially acquire novel words via a single exposure in either strongly or weakly constraining sentence contexts. We then subsequently measured behavioral and electrophysiological indices of these novel word representations using a DVF semantic priming task using lexical decision to targets that were either synonyms or unrelated in meaning to

the novel words. Our work with similar stimuli in central presentation suggests that novel words acquired in weakly constraining contexts should fail to prime in either hemisphere, indicating that a single exposure in a weak constraint context does not suffice to establish a semantic representation that can support priming in either hemisphere. In the strongly constraining condition, by contrast, we expect to see semantic priming N400 effects. Importantly, the hemisphere(s) that are implicated in our priming effects may yield important insights into the nature of these fast-mapped meanings. As described above, N400 effects in the LH would be consistent with the view that a specific definition, gloss or featural representation of the word had been acquired, whereas N400 priming effects in the RH would suggest that the fast-mapped meaning is relatively “coarse,” “event-based,” or “thematic.”

2. Method

2.1. Participants

Participants were 24 healthy adults (17 women; average age: 19.92, age range 18–24) and were given course credit or paid \$7/h for participation. All participants were right-handed, native English speakers, and had no significant exposure to another language at least before the age of 12. Participants reported no history of mental illness, learning disability, language impairment, drug abuse, or neurological trauma. All participants had normal hearing and normal (or corrected to normal) vision. An additional 14 participated but were not analyzed: 6 had excessive blinking or motion artifact, 2 because of equipment failure or experimenter error, and 6 reported a characteristic which disqualified them from analysis (3 had significant second language exposure as a child, 2 had non-normal vision, 1 was not right-handed).

2.2. Materials

Stimuli consisted of 128 sentence pairs selected from Federmeier and Kutas (1999b), and 512 word pairs selected to correspond with 128 sentence final words. Both are described in detail below.

2.2.1. Sentences

64 high constraint and 64 low constraint sentence pairs were selected from Federmeier and Kutas (1999b). The high and low constraint sentences varied in

the degree to which they led to an expectation of either a single meaning (high constraint), or to many potential meanings (low constraint), as determined by cloze procedure. These had been normed to assess cloze probability (Federmeier & Kutas, 1999b). These sentence pairs consisted of an initial sentence followed by a second that ended with a word that was either a plausible, expected sentence completion, or a pseudoword (i.e., unknown word). This yielded 32 sentences in each of four conditions: (1) High constraint/Known word ending, (2) High constraint/Unknown word ending, (3) Low constraint/Known word ending, and (4) Low constraint/Unknown word ending. Sentences were counter-balanced such that each High and Low constraint sentence pair appeared with both a Known and Unknown ending equally across all versions of the study, but not repeated within a subject. Known word target items consisted of words in 64 categories, and these target categories were used as the basis for selecting semantically related and unrelated prime–target pairs, described below. The sentence stimuli were counterbalanced across versions so that all sentences appeared with both Known and Unknown word endings with equal frequency across participants. Examples of sentence stimuli are included in Table 1a.

2.2.2. Word-pairs

512 word pairs were constructed for this study, consisting of a prime followed by a target word presented one at a time. Since repetition is known to diminish N400 effects (Besson, Kutas, & Van Petten, 1992; Van Petten et al., 1991), and it is unclear whether or not repetition would interact with factors of constraint and visual field, we designed our priming task such that the N400 of interest was to a target word that followed a Known or Unknown prime that had been initially presented in the sentence endings described above. The N400 effect of interest would thus be elicited by a previously unseen real word target (printed in all caps) while the prime stimulus was an unknown or known word that had previously appeared in the sentence endings as described above.

Target stimuli for each prime were selected for two conditions: (1) Synonym/Identical meaning (Syn/ID: lion—LION) and (2) Unrelated (Unrel: lion—CAFE). Unrelated word pairs were selected to be as closely matched as possible to the Syn/ID condition in word frequency ($F < 1$), length ($F < 1$), syllables ($F < 1$) and phonemes ($F < 1$), as reported by the MRC psycholinguistic database (Wilson, 1988). In cases where ratings on Concreteness, Familiarity and Imageability ratings were available from the MRC database, efforts were also made to match targets as closely as possible on these parameters. Additionally, targets in each condition did not differ as a function of constraint in frequency (Syn/ID: $|t| < 1$, Unrel: $t(130) = 1.057, p = 0.2924$), length [Syn/ID: $t(130) = -1.45, p = 0.148$, Unrel: $t(130) = -1.269, p = 0.2067$], number of syllables [Syn/ID: $|t| < 1$, Unrel: $|t| < 1$], and number of phonemes [Syn/ID: $t(130) = -1.36, p = 0.1775$, Unrel: $t(130) = -1.315, p = 0.1909$]. Highly associated word pairs were not included (like mouse—CHEESE, or bread—BUTTER), as confirmed via the Edinburgh Associative Thesaurus (Kiss, Armstrong, Milroy, & Piper, 1973). In cases involving Unknown word primes, the relatedness to the target (Unrelated and Synonym) was determined by the

Table 1
Examples of sentences and word pairs in each condition.

(A) Context sentences (context constraint/word type)		
Known/High	(A) Peter sat gaping at the centerfold. He asked his friend if he could borrow the MAGAZINE. (B) Tina lined up where she thought the nail should go. When she was satisfied, she asked Bruce to hand her the HAMMER.	
Unknown/High	(A) Peter sat gaping at the centerfold. He asked his friend if he could borrow the YERGE. (B) Tina lined up where she thought the nail should go. When she was satisfied, she asked Bruce to hand her the VORN.	
Known/Low	(A) The package was rectangular and heavy and suspiciously academic. Bianca was disappointed that her uncle was giving her a BOOK. (B) Pablo wanted to cut the lumber he had bought to make some shelves. He asked his neighbor if he could borrow her SAW.	
Unknown/Low	(A) The package was rectangular and heavy and suspiciously academic. Bianca was disappointed that her uncle was giving her a SHUS. (B) Pablo wanted to cut the lumber he had bought to make some shelves. He asked his neighbor if he could borrow her THANT.	
(B) Word pairs (prime–target)		
	Synonym/ID	Unrelated
Known/High	magazine—MAGAZINE	magazine—ACCIDENT
Unknown/High	hammer—HAMMER yerge—MAGAZINE vorn—HAMMER	hammer—LOCKER yerge—ACCIDENT hammer—LOCKER
Known/Low	book—BOOK saw—FACE	book—ROAD saw—SAW
Unknown/Low	shus—BOOK thant—SAW	shus—ROAD thant—FACE

Note: All word pairs were also paired with an equal number of previously unseen pseudoword (nonwords) targets, not depicted in this table. Lower case primes in the word pairs were presented centrally. Uppercase targets in the word pairs were randomly presented as left or right-lateralized. All unknown words were pronounceable pseudowords and known words were plausible and expected known word completions to the sentences. High and low constraint contexts varied on the degree to which they led to an expectation of a single meaning (high constraint) or many meanings (low constraint) as determined by cloze probability.

implied meaning of the sentence context in which the Unknown word had previously appeared.

An equal number of Nonword targets were also constructed so that approximately half of the lexical decisions should be “No.” Nonwords were constructed using the ARC Nonword database (Rastle, Harrington, & Coltheart, 2002), and were selected to be pronounceable, conform to English phonotactics, and contain between 4 and 7 letters. It should be noted that these “Nonwords” did not appear in the sentence contexts, unlike the pseudowords presented in the Unknown word condition, and thus it would be reasonable to expect that participants would provide a “No” lexical decision in response to them. The proportion of targets in each condition is as follows: Nonwords=1/2, Syn/ID=1/4, Unrel=1/4, which appeared in each hemifield.

With this arrangement, any Known or Unknown prime was equally likely to precede a lateralized Syn/ID or Unrel target in one of four conditions: (1) Syn/Id—LVF, (2) Syn/ID—RVF, (3) Unrel—LVF, (4) Unrel—RVF (see Table 1b for examples or prime–target pairs in each condition). In each version, each of (Known and Unknown) prime words appeared in a pseudo-random combination of three of these four possible target conditions. All possible combinations appeared across all versions with equal frequency, ensuring that all possible prime–target pairings appeared with equal frequency across all versions.

2.3. Procedure

Participants were tested in a single experimental session conducted in a sound-proof, electrically-shielded chamber and were seated in a comfortable chair in front of a monitor. Sessions consisted of two interleaved tasks: sentence comprehension and priming. A schematic outline of these two tasks is shown in Fig. 1.

In the sentence comprehension task, participants were instructed to read the context sentences and to do their best to understand the sentence and words even when nonsense words appeared. The first sentence in the pair was presented in its entirety on the monitor; participants were instructed to press a button when they had completed reading this sentence and were ready to see the second sentence. The second sentence was preceded by a series of crosses (500 ms duration with a stimulus-onset-asynchrony varying randomly between 300 and 800 ms) to orient the participant to the center of the screen. Sentences were then presented one word at a time, each for 200 ms with a stimulus-onset-asynchrony of 500 ms. Participants were asked to minimize blinking and movement during sentence presentation. The final target word appeared on the screen for 1400 ms.

In the priming task, participants were instructed to read every word that appeared on the screen and indicate with a button press if the target items (which were identified by appearing in capital letters) were or were not real words.

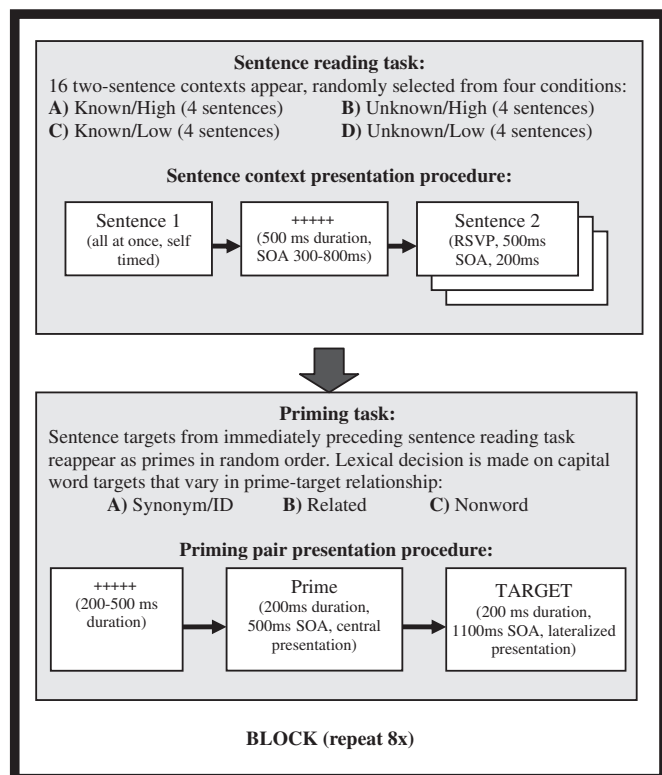


Fig. 1. Schematic description of experimental procedure for a single block. See Table 1 for examples of stimuli in each condition.

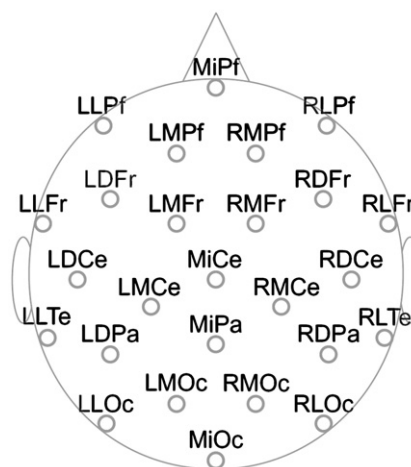


Fig. 2. Diagram of electrode positions and labels.

Participants viewed two sets of prime/target pairs, and were given a 2500 ms break period between pairs. Prime pair onsets were preceded by a set of fixation crosses that were presented randomly between 200 and 500 ms. A central fixation dot appeared on the screen throughout the trials positioned at a half degree immediately below the centrally presented prime words and fixation crosses. Immediately following the fixation cross, a prime word appeared centrally in lower case letters for 200 ms, followed by an offset of 300 ms, followed by the uppercase target word that appeared in the left or right visual field with the inner edge 2° of visual angle from fixation for 200 ms, and offset of 800 ms. Participants provided a lexical decision response as soon as possible after the presentation of each target word in capital letters.

Sentence comprehension and priming tasks were interleaved as follows. Participants read 16 sentence pairs, and then completed the priming task consisting of 96 pairs, with each prime being selected six times in random order from the 16 sentence endings that had just been previously read. Participants were given a break before beginning a new block of sentences. The entire experiment consisted of 8 blocks of sentence/prime sets. At the end of the study, participants were asked to complete a surprise old/new recognition memory questionnaire containing 50 sentences that had appeared in the study, and 50 new sentences that had not. This was given to ensure that participants had sufficiently attended to the sentences.

2.4. Electrophysiological recording

Scalp potentials were continuously recorded with a left mastoid reference from 26 geodesically arranged sites embedded in an ElectroCap with tin electrodes. Electrodes were placed at equal distances across the scalp, with positions and labels shown in Fig. 2. Horizontal eye movements were monitored via electrodes placed on the outer canthus, with the left electrode as a reference. Blinks were monitored via electrodes placed on the infraorbital ridge of each eye, with each electrode referenced to the left mastoid. Potentials were digitized at a sampling rate of 250 Hz and hardware bandpass filter of 0.1–100 Hz with Grass Amplifiers and stored on a hard disk for later analysis. Impedances were kept below 5 kΩ. The ERPs were stimulus-locked averages consisting of a 100-ms baseline and a 920 post-stimulus interval.

2.5. Data analysis

Data were re-referenced offline to an average left and right mastoid. Trials contaminated by eye movements, blinks, excessive muscle activity, or amplifier blocking were rejected offline before averaging. ERPs were computed for epochs extending from 100 ms before stimulus onset to 920 ms after stimulus onset. Averages of artifact-free ERP trials were computed to targets in all priming conditions in both the RVF/LH and LVF/RH: Identical/Synonym and Unrelated targets for each of the four main conditions High/Known, High/Unknown, Low/Known, Low/Unknown after subtraction of the 100 ms pre-stimulus baseline.

3. Results

3.1. Behavioral responses

3.1.1. Accuracy

Mean accuracy scores are shown in Fig. 3 and Table 2. A four-factor repeated measures ANOVA with factors of Word type

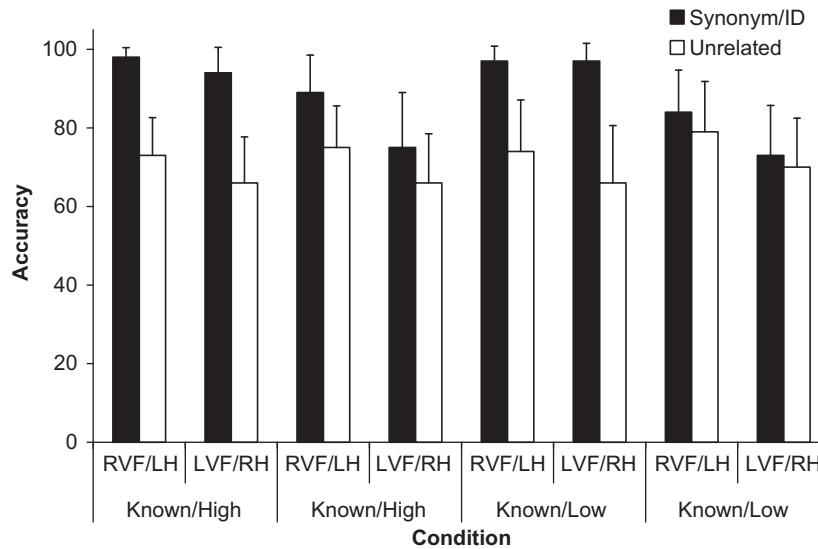


Fig. 3. Mean accuracy of behavioral responses across experimental conditions.

(Known and Unknown), Constraint (Low and High), Visual Field (LVF and RVF) and Prime relationship (Synonym/ID and Unrelated) revealed significant main effects of Word Type [$F(1,23)=34.68$, $p < 0.0001$], with lower accuracies for targets preceded by Unknown words, Visual Field [$F(1,23)=53.55$, $p < 0.0001$], with higher accuracies for words presented to the RVF/LH, and Prime relationship [$F(1,23)=169.89$, $p < 0.0001$], with higher accuracies observed when targets were preceded by a word that was related in meaning. There were significant interactions of Word Type \times Visual Field [$F(1,23)=14.52$, $p=0.0009$], Word Type \times Prime Relationship [$F(1,23)=100.19$, $p < 0.0001$] and Word Type \times Prime Relationship \times Visual Field [$F(1,23)=10.53$, $p=0.0036$]. Marginal interactions of Visual Field \times Prime [$F(1,23)=4.18$, $p=0.0524$] and Word Type \times Constraint \times Prime [$F(1,23)=3.88$, $p=0.0611$] were also observed. Follow-up Tukey-test comparisons revealed more correct responses to targets when presented to the RVF, for both Known and Unknown word primes, and that Targets that were related to Known and Unknown word prime meanings also elicited higher accuracies (all $p < 0.05$). The three-way Word Type \times Constraint \times Prime interaction was driven by a failure to find an effect of priming for Unknown words that initially appeared in Low constraint contexts; all other prime word conditions (Unknown/High, Known/High and Known/Low) showed reduced accuracies to targets that were unrelated in meaning (all $p < 0.05$). Additional Tukey tests also revealed that the three-way Word Type \times Visual Field \times Prime interaction was driven by an absence of a priming effect for Unknown words in the LVF/RH, while all other conditions (Known/RVF, Known/LVF, Unknown/RVF) showed reduced accuracies to unrelated target words (all $p < 0.05$). In sum, higher accuracies were observed for words that appeared in the RVF/LH compared to the LVF/RH, and for targets preceded by Known, compared to Unknown words. In general, accuracies were reduced when primed by words that were unrelated in meaning, except when preceded by Unknown words that initially appeared in low constraint contexts.

3.1.2. Reaction time

Mean reaction times for correct responses are shown in Fig. 4 and Table 2. A four-factor repeated measures ANOVA was carried out with factors of Word type (Known and Unknown), Constraint (Low and High), Visual Field (LVF and RVF) and Prime relationship

(Synonym/ID and Unrelated). This analysis revealed significant main effects of Word Type [$F(1,23)=136.66$, $p < 0.0001$], with faster RTs for targets preceded by known words, Visual Field [$F(1,23)=26.59$, $p < 0.0001$], faster RTs for targets presented in the RVF/LH, and Prime [$F(1,23)=170.44$, $p < 0.0001$], and slower RTs to targets preceded by unrelated words. Interactions of Word Type \times Prime [$F(1,23)=96.01$, $p < 0.0001$], Visual Field \times Prime [$F(1,23)=7.36$, $p=0.0124$], Word Type \times Constraint \times Prime [$F(1,23)=5.53$, $p=0.0277$], Word Type \times Constraint \times Visual Field [$F(1,23)=7.38$, $p=0.0123$]. A marginal effect of Constraint \times Visual Field was also observed [$F(1,23)=3.98$, $p=0.0581$]. Follow-up Tukey test comparisons revealed that these interactions were driven by a lack of priming effect for targets that were preceded by Unknown words. In addition, targets preceded by both Unknown/High and Unknown/Low words did not show priming effects. Significant effects of priming were observed in both visual fields, and as expected, for targets preceded by Known words that had appeared in both High and Low constraint contexts (all $p < 0.05$). In sum, robust priming effects were found for Known words that had initially appeared in sentences of both High and Low constraint, however, priming effects were not found for targets preceded by Unknown words.

3.2. Electrophysiological responses

Artifact-free correct responses to target words in eight priming conditions were analyzed, four each in the RVF/LH and LVF/RH conditions: Known/Related, Known/Unrelated, Unknown/Related, Unknown/Unrelated. Grand average ERPs across all electrodes to target words in all eight conditions are shown in Figs. 6–9 and at a single electrode, the vertex, in Fig. 10. As can be seen from these figures, an effect of target type is seen in all four Known word priming conditions, and in one Unknown word priming condition, represented by a modulation of a negative-going peak ranging between 250 and 500 ms (N400), followed by a continuing positivity between 500 and 900 ms (LPC). We analyzed the ERP across three time windows corresponding to the N1 component (100–200 ms), N400 (250–500 ms), and LPC (500–900 ms)

3.2.1. N1 amplitude

In order to ensure that initial processing of the target words was conducted by the contralateral hemisphere, we examined the N1,

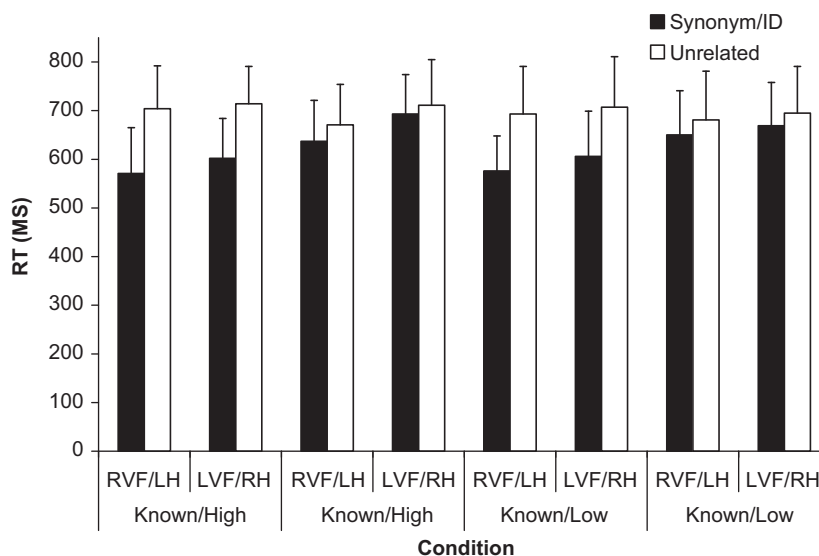


Fig. 4. Mean reaction time of behavioral responses across experimental conditions.

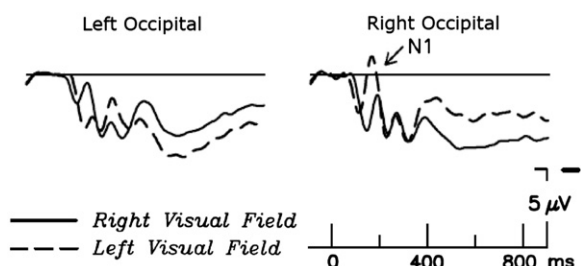


Fig. 5. Effect of stimulus lateralization on the ERP. ERPs are plotted across two electrodes where N1 effects of typically largest as a function of visual field of stimulus presentation, collapsed across constraint, prime relationship, and word type. N1 responses (100–200 ms) are largest in the contralateral field of stimulus presentation.

which is thought to reflect initial perception and awareness of visual stimuli. Mean amplitude N1 responses were measured across 10 posterior electrodes (5 in each hemisphere), where N1 effects are typically largest, between 100 and 200 ms to correct responses in all experimental conditions. The Left hemisphere electrodes were: LLOc, LLTe, LMOC, LDPa and LDCE, and corresponding Right hemisphere electrodes were: RLOc, RLTe, RMOc, RDPa, and RDCe. Fig. 5 shows the effect of visual field on presentation at LLOc and RLOc. A two-factor repeated measures ANOVA was conducted with factors of VF (LVF and RVF), and Hemisphere (measured at RH or LH electrodes). This analysis revealed main effects of Hemisphere [$F(1,23)=28.48, p < 0.0001$] and VF [$F(1,23)=6.84, p < 0.0089$], and a significant interaction of Hemisphere and VF [$F(1,23)=153.10, p < 0.0001$]. Follow-up Tukey tests revealed that N1 amplitudes were larger (more negative) over the contralateral hemisphere of visual presentation (mean amplitude for RVF in LH: 1.58 μ V and RH: 2.16 μ V, and for LVF presentation in LH: 2.38 μ V and RH: 0.92 μ V), and that the largest N1 amplitudes in each hemisphere were evoked by stimuli from the contralateral hemisphere (mean N1 amplitude over LH in RVF: 1.58 μ V and LVF: 2.38 μ V and in over RH in RVF: 2.16 μ V and LVF: 0.92 μ V).

3.2.2. N400 amplitude

Mean N400 amplitudes were measured between 250 and 500 ms across all 26 channels to correct responses. A repeated

measures ANOVA was conducted with factors of Word Type (Known and Unknown) \times Constraint (High and Low) \times Visual Field (LVF/RH, and RVF/LH), Prime Relatedness (Synonym/ID and Unrelated) and Channel (26 levels of electrode). Significant effects in this analysis are summarized in Table 3. To better understand the four-way priming effects across Word Type, Constraint, Visual Field and Prime Relatedness, we carried out planned comparisons of N400 priming effects in all conditions: (1) Known/High/RVF, (2) Known/High/LVF, (3) Known/Low/RVF, (4) Known/Low/LVF, (5) Unknown/High/RVF, (6) Unknown/High/LVF, (7) Unknown/Low/RVF, and (8) Unknown/Low/LVF (Table 4). As shown in Table 4, significant priming effects were observed for all Known word conditions, but priming effects for Unknown words only appeared for Unknown/High primes in the LVF. No other priming effects in the N400 time window were observed.

3.2.3. N400 distribution

The channel factor yielded several main effects and interactions in the previous analysis. We therefore conducted additional analyses to explore whether or not these N400 priming effects had the same scalp topographies across conditions. These analyses were conducted over the N400 time-window (250–500 ms) across 16 electrodes: LLPf, RLPf, LMPf, RMPf, LLFr, RLFr, LMFr, RMFr, LLTe, RLTe, LMCE, RMCE, LLOc, RLOc, LMOc, RMOc (see Federmeier et al., 2005) classified according to Hemisphere (Right or Left), Anteriority (Prefrontal, Frontal, Central, Occipital), Laterality (Medial or Lateral). A repeated measures ANOVA was conducted with experimental factors of Word Type (Known and Unknown) \times Constraint (High and Low) \times Visual Field (LVF/RH, and RVF/LH), and Prime Relatedness (Synonym/ID and Unrelated), and distributional electrode factors of Hemisphere (Right and Left), Anteriority (Prefrontal, Frontal, Central, Occipital) and Laterality (Medial and Lateral). Main effects and interactions of this analysis are listed in Table 5. Overall, main effects and interactions of distributional factors were driven by a tendency for the N400 to be larger in the right hemisphere, over central and lateral scalp locations. An interaction of Visual Field \times Hemisphere was driven by larger N400 amplitudes to stimuli presented in the LVF/RH over RH electrode sites compared to stimuli presented to the RVF/LH. There was also an additional interaction of Visual Field \times Hemisphere \times Laterality that was driven by larger N400 amplitudes for stimuli presented to the LVF/RH, except at left lateral electrodes. Despite there being a significant four-way

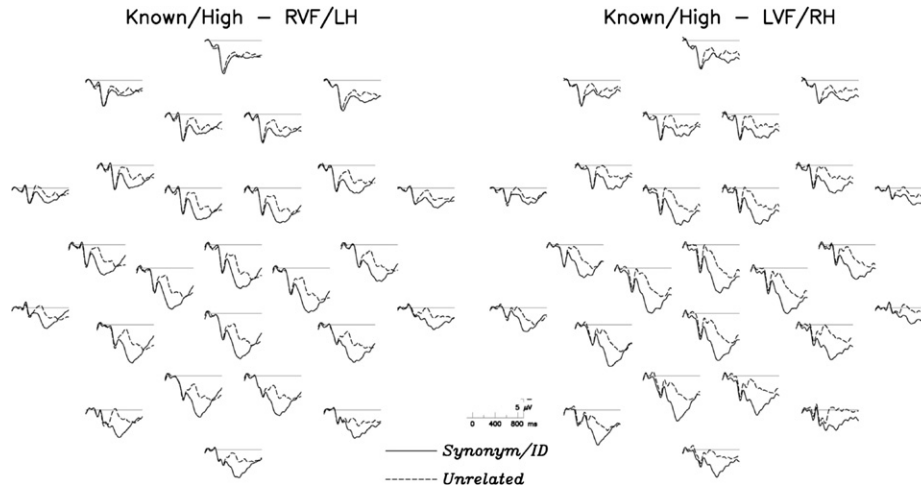


Fig. 6. Grand average ERPs across all subjects and electrode sites for targets presented to RVF/LH and LVF/RH that were preceded by Known primes presented in High constraint sentence contexts.

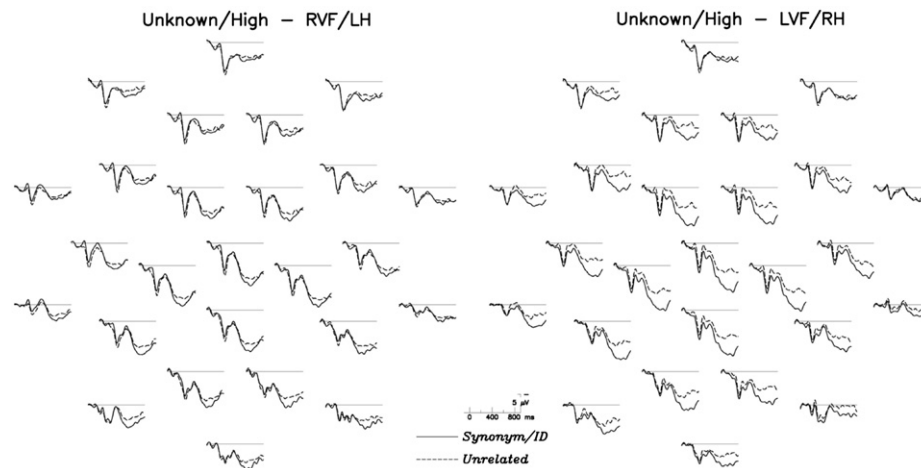


Fig. 7. Grand average ERPs across all subjects and electrode sites for targets presented to RVF/LH and LVF/RH that were preceded by Unknown primes presented in High constraint sentence contexts.

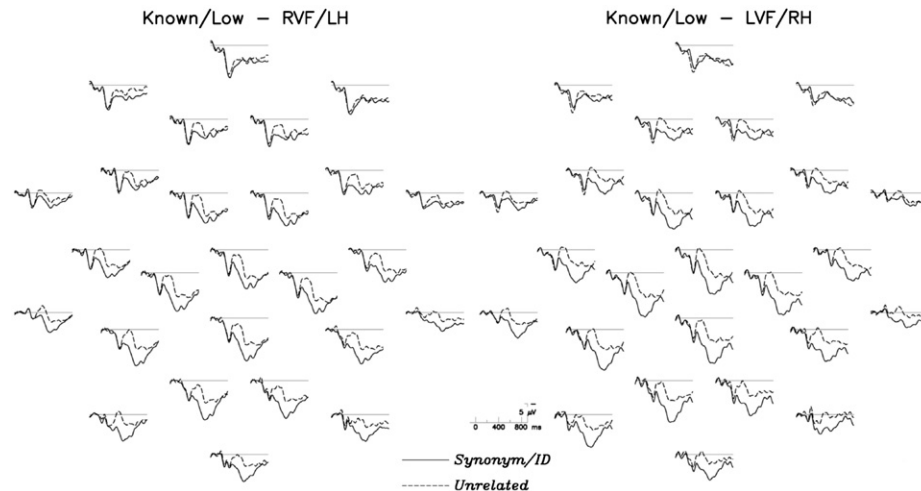


Fig. 8. Grand average ERPs across all subjects and electrode sites for targets presented to RVF/LH and LVF/RH that were preceded by Known primes presented in Low constraint sentence contexts.

interaction between experimental factors (as observed in the above amplitude analyses across a more restricted set of channels), no interactions were found between this four-way combination of

experimental factors and any individual distributional factors, or combination of distributional factors, indicating that experimental priming effects did not have differential distributions.

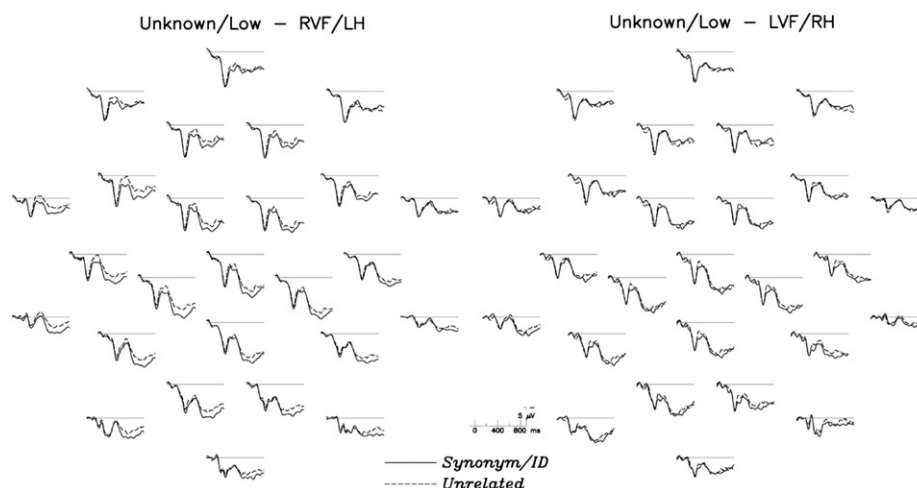


Fig. 9. Grand average ERPs across all subjects and electrode sites for targets presented to RVF/LH and LVF/RH that were preceded by Unknown primes presented in Low constraint sentence contexts.

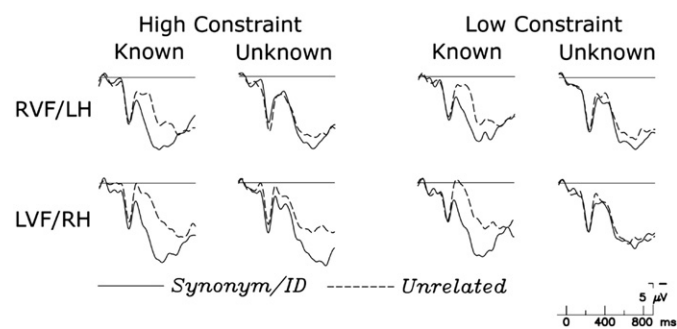


Fig. 10. Grand average ERPs to target words in priming task at a single electrode, MiCE.

3.2.4. LPC amplitude

In addition to experimental effects observed in the traditional N400 time window between 250 and 500 ms, there were extended priming effects that continued through the 900 ms epoch. We measured these late effects by calculating the mean LPC amplitude from a period between 500 and 900 ms across all 26 electrodes for correct responses. A repeated measures ANOVA was conducted with factors of Word Type (Known and Unknown) \times Constraint (High and Low) \times Visual Field (LVF/RH, and RVF/LH), Prime Relatedness (Synonym/ID and Unrelated) and Channel (26 levels of electrode), and is summarized in Table 3. As with the N400 analysis, follow-up comparisons were conducted in order to quantify the extent of late priming effects across experimental conditions. Synonym/ID and Unrelated LPC mean amplitude was compared across eight experimental conditions: (1) Known/High/RVF, (2) Known/High/LVF, (3) Known/Low/RVF, (4) Known/Low/LVF, (5) Unknown/High/RVF, (6) Unknown/High/LVF, (7) Unknown/Low/RVF, and (8) Unknown/Low/LVF. Significant LPC priming effects were found for all conditions except one: Unknown/Low/LVF (effects listed in Table 4).

3.2.5. LPC distribution

In order to characterize the distribution of the LPC effect, additional analyses were carried out within the LPC time window (between 500 and 900 ms) over 16 electrodes, classified according to scalp location, as described in the earlier N400 distributional analyses. We carried out a repeated-measures ANOVA with experimental factors of Word Type (Known and Unknown) \times Constraint (High and Low) \times Visual Field (LVF/RH, and RVF/LH),

and Prime Relatedness (Synonym/ID and Unrelated), and distributional electrode factors of Hemisphere (Right and Left) \times Anteriority (Prefrontal, Frontal, Central, Occipital) \times Laterality (Medial and Lateral). The findings of this analysis are summarized in Table 5. Main effects and interactions were driven by larger (more positive) LPC amplitudes in electrodes over the medial electrodes in contralateral hemisphere of the visual field of the stimulus, and by larger posterior LPC effects at posterior sites for stimuli presented to the RVF/LH, compared to those shown to the LVF/RH. Distributional main effects were driven by a tendency for the LPC to be largest over Left/Medial Frontal, Central and Posterior electrode sites, and smaller at Prefrontal and Lateral regions on the scalp. Like in the previous analysis, there was a four-way interaction between Prime Relatedness, Word Type, Constraint and Visual Field, but there were no further interactions between these four experimental factors and any single distributional factor or combination of distributional factors, suggesting that the LPC distribution of the priming effects observed was equivalent across experimental conditions.

4. Discussion

Previous work has found that a single presentation of a novel word in a highly constraining sentential context can result in an appreciation of aspects of its meaning and usage, as reflected in electrophysiological measures of modulations in the amplitude of the N400 ERP component. The aim of this study was to examine how this rapidly acquired representation of word meaning may be distributed across the cerebral hemispheres.

Our behavioral results replicated a number of standard findings. First, faster reaction times and increased accuracies were observed for targets presented to the RVF/LH compared to the LVF/RH. This is a well-documented outcome of the lateralized lexical priming task, and is consistent with an overall left hemisphere advantage for the lexical decision task. In addition, as expected, we found standard priming effects for known words across both hemispheres. Known word primes that were identical to the target words yielded faster and more accurate responses to targets in both hemispheres compared to those that were unrelated in meaning. This is consistent with studies reporting repetition priming in the left and right hemispheres (Marsolek, Kosslyn, & Squire, 1992; Weems & Zaidel, 2005).

By contrast, consistent behavioral priming effects were not observed for Unknown word primes. While reaction time measures

Table 2
Mean percentage of correct responses and mean reactions times (ms) for priming task in all conditions.

	Known/High		Unknown/High		Known/Low		Unknown/Low	
	RVF/LH	LVF/RH	RVF/LH	LVF/RH	RVF/LH	LVF/RH	RVF/LH	LVF/RH
<i>Accuracy</i>								
Synonym/ID	98 (2.4)	94 (6.5)	89 (9.5)	75 (14.0)	97 (3.8)	97 (4.5)	84 (10.7)	73 (12.7)
Unrelated	73 (9.6)	66 (11.7)	75 (10.6)	66 (12.5)	74 (13.1)	66 (14.6)	79 (12.8)	70 (12.5)
<i>RT (ms)</i>								
Synonym/ID	571 (94)	602 (82)	637 (84)	693 (81)	576 (72)	606 (93)	650 (91)	669 (89)
Unrelated	704 (88)	714 (77)	671 (83)	711 (94)	693 (98)	707(104)	681(100)	695 (96)

Note: Standard deviations are reported in parentheses.

Table 3
F-values of significant N400 and LPC priming effects.

	Df	N400 amplitude		LPC amplitude	
		F	P <	F	P <
Constraint (C)	(1,23)	4.94	0.0263	30.98	0.0001
Prime Relatedness(P)	(1,23)	1267.1	0.0001	623.92	0.0001
Word type (W)	(1, 23)	73.59	0.0001	67.25	0.0001
Visual Field (V)	(1,23)	141.9	0.0001	14.36	0.0001
Channel (Ch)	(25,575)	56.53	0.0001	147.63	0.0001
C × P	(1,23)			25.68	0.0001
C × W	(1,23)	40.66	0.0001		
C × V	(1,23)	4.26	0.0001		
P × W	(1,23)	536.6	0.0001		
P × V	(1,23)	16.77	0.0001	18.74	0.0001
P × Ch	(25,575)	5.53	0.0001	3.36	0.0001
W × V	(1,23)			7.96	0.0001
V × Ch	(25,575)	3.35	0.0001	6.64	0.0001
C × P × W	(1,23)	7.23	0.0072	4.21	0.0402
C × P × V	(1,23)	12.74	0.0001	33.25	0.0001
P × W × V	(1,23)			4.29	0.0385
P × W × Ch	(25,575)	3.09	0.0001		
C × P × W × V	(1,23)	6.99	0.0001	18.16	0.0001

Interactions that did not yield significant N400 or LPC effects are omitted.

Table 4
F-values from pairwise ANOVAs comparing mean N400 and LPC amplitude to unrelated and synonym/ID targets in prime conditions across visual fields.

	N400 comparisons		LPC comparisons	
	RVF/LH	LVF/RH	RVF/LH	LVF/RH
Known/High	28.49***	62.84***	7.58*	28.95***
Known/Low	16.57**	25.29***	5.97*	11.89**
Unknown/High	ns	12.64**	8.46**	24.78***
Unknown/Low	ns	ns	8.99**	ns

* Statistical significance at $p < 0.05$.

** Statistical significance at $p < 0.01$.

*** Statistical significance at $p < 0.0001$.

failed to reveal priming effects for Unknown words in any condition, replicating prior reports in centralized priming studies (Borovsky et al., 2012), our accuracy analyses revealed priming effects for Unknown words acquired under High constraint conditions. This discrepancy between lateralized and central priming tasks in accuracy indicates that ceiling effects in the centralized task may have masked behavioral sensitivity to the priming relationship.

Our electrophysiological findings also replicated a number of standard results. For one, the visual occipital N1 component was larger over electrodes contralateral to the visual field of stimulus presentation. This indicates that our paradigm was successful in directing stimuli (initially) to a single hemisphere. Additionally, we found a number of typical N400 priming effects for stimuli

Table 5
F-values of significant N400 and LPC priming effects in distributional analyses.

	Df	N400 effects		LPC effects	
		F	P <	F	P <
Constraint (C)	(1,23)			16.07	0.0001
Prime Relatedness(P)	(1,23)	703.22	0.0001	340.86	0.0001
Word type (W)	(1,23)	42.08	0.0001	35.88	0.0001
Visual Field (V)	(1,23)	81.98	0.0001	6.58	0.0103
Hemisphere (H)	(1,23)	9.80	0.0018		
Anteriority (A)	(3,69)	69.38	0.0001	97.66	0.0001
Laterality (L)	(1,23)	483.95	0.0001	1464.21	0.0001
C × W	(1,23)	21.13	0.0001		
P × C	(1,23)			15.74	0.0001
P × W	(1,23)	291.70	0.0001	11.69	0.0006
P × V	(1,23)	7.87	0.0051	7.90	0.005
P × A	(3,69)	10.96	0.0001	315.38	0.0001
P × L	(1,23)	54.96	0.0001	17.26	0.0001
W × V	(1,23)			3.96	0.0468
W × L	(1,23)			6.48	0.0109
V × A	(3,69)			3.80	0.0265
V × H	(1, 23)	48.68	0.0001	76.30	0.0001
H × A	(3,69)	3.77	0.0102	751.07	0.0001
H × L	(1,23)			3.85	0.0499
A × L	(3,69)	109.36	0.0001	145.38	0.0001
C × P × V	(1,23)			20.19	0.0001
P × W × A	(3,69)	8.49	0.0001		
P × W × L	(1,23)	21.57	0.0001		
P × V × L	(1,23)	5.15	0.0233	7.02	0.0081
V × H × A	(3,69)			9.03	0.0001
V × H × L	(1,23)	12.73	0.0004	14.21	0.0002
H × A × L	(3,69)			6.48	0.0002
C × P × W × V	(1,23)	3.99	0.046	10.15	0.0014
V × H × A × L	(3,69)			2.77	0.0402

Interactions that did not yield significant N400 or LPC effects are omitted.

presented to both hemispheres. N400 amplitudes were reduced when targets were preceded by Known words that were identical to it (including but not limited to in meaning).

Although our N400 results were consistent with our behavioral results for Known words, they were notably different for Unknown word priming. We found robust ERP priming effects for targets preceded by Known words regardless of hemisphere of target presentation. Differences due to prime relationship extended between 250 and 900 ms, encompassing both the N400 and LPC time windows. In both time windows and hemispheres we observed typical priming effects: Less negative amplitudes were measured for target words identical or related to primes. In addition, the scalp topography of these priming effects did not vary across experimental conditions.

In the N400 time window, Unknown word priming was observed only when target words initially presented to the LVF/RH were preceded by Unknown words that had initially appeared in strongly constrained contexts. Unknown words from weakly constrained contexts were not effective primes for target words

appearing in either visual field. These right-lateralized N400 effects resembled ERP findings with central field presentation, but were smaller in magnitude (Borovsky et al., 2012). Our findings suggest that the N400 effects observed with central visual presentation may have been primarily driven by representations encoded by the right hemisphere. Although smaller in magnitude than the central N400 effects, the scalp topography of the N400 priming effect from Unknown/High constraint words in the LVF/RH was the same as that of the other prime conditions. Although scalp topographies are limited indicators of neural generators given the inverse problem, the similarity of N400 priming effect topographies across conditions suggest as a first pass that there is no need to invoke different generators for the central and right hemisphere known or unknown word effects.

Unlike our prior study using central primes and targets (Borovsky et al., 2012), we saw sizeable posterior LPC priming effects in this lateralized task. For the most part, the LPC effects tracked that of the N400; Known word primes that were identical to the target elicited larger positivities than those that were unrelated in meaning in all Known word conditions, and Unknown words that initially appeared in strongly constrained contexts elicited LPC priming effects in the RH. But interesting differences existed between N400 and LPC effects for the Unknown word conditions. Most notably, we found LPC priming effects in the LH for Unknown/High and Unknown/Low conditions, when N400 priming effects were not found in these conditions. These discrepancies in our LPC effects raises two questions: (1) Why do we see LPC priming effects in the lateralized task but not the centralized version, and (2) Why do LPC priming effects appear in the LH in cases where the N400 priming effects do not? In respect to the first question, it should be noted that extended LPC effects are not uncommon in DVF semantic priming tasks (e.g. Bouaffre & Faita-Ainseba, 2007; Coulson et al., 2005). Also, the ERP effects appear later in the lateralized vs. centralized version. It is possible that the mechanisms that underlie the observed LPC effects may overlap with the N400 component in the centralized version, thereby masking separable LPC effects. However, it should be noted that language processing under most circumstances involves rapid and complex communication between the hemispheres. In a DVF task, this normal intercommunication is briefly disrupted, which may result in measurements of electrical brain activity that do not neatly sum to yield central effects.

Next, we consider two accounts to address our second question concerning differential priming patterns between the N400 and LPC. One influential account of the LPC has linked it with strategic, conscious, or controlled cognitive processing tasks that involve retrieval of information from memory (Olichney et al., 2000; Rugg & Curran, 2007; Van Petten et al., 1991). In our task, participants may have detected and considered the relationship between prime and target pairs, yielding more extensive, bilateral priming effects in the later occurring LPC component. This explanation may explain why we saw larger LPC effects for repeated Known words, compared to Unknown word synonyms, in which the semantic link between the prime and target may have been weaker. Even so, it is not apparent why this effect may have appeared in the lateralized but not central version of this task. Another possibility, consistent with the PARLO framework of hemispheric meaning processing (Production Affects Reception in Left Only; Federmeier, 2007) is that the LH may be engaged in predictive, “top-down,” or controlled semantic processing, whereas the RH may integrate meaning in a more “bottom-up” fashion. Consistent with this account, Kandhadai and Federmeier (2010) observe larger LPC backwards priming effects in the LH vs. RH, but equivalent priming effects across the hemispheres in a forward priming condition. One explanation for this effect is that the LH was additionally involved in strategic activation of prime–target meaning relationships when the connection between the

prime and target is weak. This type of process may explain why LPC priming effects in the LH for Unknown/Low words in our study, although further investigation would be necessary to evaluate this account.

Since N400 priming effects were noted only for Unknown (recently learned)/High constraint word stimuli flashed initially in the left visual field (i.e., right hemisphere), it is reasonable to hypothesize that rapidly acquired representations of novel word meanings may be initially integrated into semantic memory via the right hemisphere. Our results are consistent with previous findings from the developmental literature, which have observed increased deficits in vocabulary acquisition in children who have obtained early injury to the right hemisphere (Eisele & Aram, 1993; Thal et al., 1991), as well as ERP studies that find greater bilateral activity at early stages of language learning (Mills et al., 1993). This suggests that the neural mechanisms invoked in the earliest examples of word learning in infancy may also extend to adults.

Prior work on hemispheric representation of word meaning has characterized left hemisphere representations as “focused”, “fine” or “localized”, in contrast with “coarse”, “diffuse”, or “distributed” representations in the right hemisphere (Beeman et al., 1994; Chiarello, 1998; Grose-Fifer & Deacon, 2004). In our study, it is possible that the initial representations that are established after a single presentation of a word in context may not have yet developed a specific, fine-grained structure that has been proposed as characteristic of the left hemisphere. Conceivably, such representations might require additional use with any given new word in many different contexts. Ince and Christman’s (2002) work on hemispheric representation of low familiarity words suggests a more specific mechanism of how hemispheric involvement in word representation may change with experience. They propose that novel word meanings may be initially represented “thematically” in the right hemisphere via apprehension of the relevant lexical and event associations that co-occur with a novel meaning. As this knowledge accrues with additional experience, categorical knowledge may be gained by the left hemisphere indirectly. If so, this indicates that the right hemisphere may initially represent word meanings from context in single-trial learning, but that the left hemisphere is recruited with continued experience and increased knowledge of the word. Importantly, it also suggests that this right-to-left shift should be associated with a thematic-to-categorical shift in the semantic representation of a novel word. This hypothesis merits further study.

Neuropsychological studies of narrative and discourse processing in patient populations have also highlighted the importance of the right hemisphere. In this area, a number of studies have found that patients with right hemisphere brain injuries have relative difficulty in connecting extended narrative passages or discourse context, and that these deficits potentially stem from problems in inferring appropriate meanings from these contexts (Beeman, 1993; Tompkins, Scharp, Meigh, & Fassbinder, 2008). In our study, participants needed to rapidly integrate information from sentence contexts to infer appropriate meanings of novel words. Thus, it is possible that the involvement of the right hemisphere in priming of unknown word meanings could be related to the RH involvement of inferring appropriate meaning from context, but further work is necessary to test this idea.

In summary, this study is the first to examine the differential involvement of the cerebral hemispheres during acquisition of word meaning. Our electrophysiological results suggest that novel word meanings initially experienced in highly constraining contexts first prime semantically related meanings in the right hemisphere. This work complements and extends previous findings that the N400 component in young adults is sensitive to

acquisition of novel word meaning after only a single exposure in a highly constraining context. Thus, while previous studies have observed electrophysiological evidence of novel word priming after a single instance, the present study suggests that this priming effect may be driven primarily by the right hemisphere.

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References

- Abernethy, M., & Coney, J. (1996). Semantic category priming in the left cerebral hemisphere. *Neuropsychologia*, 34(5), 339–350.
- 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(2), 177–190.
- Anglin, J. M. (1993). Vocabulary development: A morphological analysis. *Monographs of the Society for Research in Child Development*, 58 (10, Serial no. 238).
- Batterink, L., & Neville, H. (2011). Implicit and explicit mechanisms of word learning in a narrative context: An event-related potential study. *Journal of Cognitive Neuroscience*, 23(11), 3181–3196.
- Beeman, M., & Chiarello, C. (Eds.). (1998). Mahwah, NJ, US: Lawrence Erlbaum Associates, Inc., Publishers.
- Beeman, M., Friedman, R. B., Grafman, J., & Perez, E. (1994). Summation priming and coarse semantic coding in the right hemisphere. *Journal of Cognitive Neuroscience*, 6(1), 26–45.
- Beeman, M. (1993). Semantic processing in the right hemisphere may contribute to drawing inferences from discourse. *Brain and Language*, 44, 80–120.
- Bentin, S. (1987). Event-related potentials, semantic processes, and expectancy factors in word recognition. *Brain & Language*, 31(2), 308–327.
- Bentin, S., McCarthy, G., & Wood, C. C. (1985). Event-related potentials associated with semantic priming. *Electroencephalography and Clinical Neurophysiology*, 60, 343–355.
- Besson, M., Kutas, M., & Van Petten, C. (1992). An event-related potential (ERP) analysis of semantic congruity and repetition effects in sentences. *Journal of Cognitive Neuroscience*, 4(2), 132–149.
- Borovsky, A., Elman, J., & Kutas, M. (2012). Once is enough: N400 indexes semantic integration of novel word meanings from a single exposure in context. *Language Learning and Development*, 8(3), 278–302.
- Borovsky, A., Kutas, M., & Elman, J. (2010). Learning to use words: Event-related potentials index single-shot contextual word learning. *Cognition*, 116(2), 289–296.
- Bouaffre, S., & Fajta-Ainseba, F. (2007). Hemispheric differences in the time-course of semantic priming processes: Evidence from event-related potentials (ERPs). *Brain and Cognition*, 63(2), 123–135.
- Breitenstein, C., Jansen, A., Deppe, M., Foerster, A. F., Sommer, J., Wolbers, T., et al. (2005). Hippocampus activity differentiates good from poor learners of a novel lexicon. *Neuroimage*, 25(3), 958–968.
- Brown, C., & Hagoort, P. (1993). The processing nature of the N400—Evidence from masked priming. *Journal of Cognitive Neuroscience*, 5(1), 34–44.
- Burgess, C., & Simpson, G. B. (1988). Cerebral hemispheric mechanisms in the retrieval of ambiguous word meanings. *Brain & Language*, 33(1), 86–103.
- Carey, S., & Bartlett, E. (1978). Acquiring a single new word. *Papers and Reports on Child Language Development*, 15, 17–29.
- Chiarello, C. (1998). On codes of meaning and the meaning of codes: Semantic access and retrieval within and between hemispheres. In: M. Beeman, & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 141–160). Mahwah, NJ: Lawrence Erlbaum Associates.
- Chiarello, C., Burgess, C., Richards, L., & Pollock, A. (1990). Semantic and associative priming in the cerebral hemispheres: Some words do, some words don't... sometimes, some places. *Brain & Language*, 38(1), 75–104.
- Chiarello, C., & Richards, L. (1992). Another look at categorical priming in the cerebral hemispheres. *Neuropsychologia*, 30(4), 381–392.
- Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, 82(6), 407–428.
- Coulson, S., Federmeier, K. D., Van Petten, C., & Kutas, M. (2005). Right hemisphere sensitivity to word and sentence level context: Evidence from event-related brain potentials. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 31(1), 129–147.
- Coulson, S., & Williams, R. F. (2005). Hemispheric asymmetries and joke comprehension. *Neuropsychologia*, 43(1), 128–141.
- Davis, M. H., & Gaskell, M. G. (2009). A complementary systems account of word learning: Neural and behavioural evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1536), 3773–3800.
- Deacon, D., Grose-Fifer, J., Yang, C.-M., Stanick, V., Hewitt, S., & Dynowska, A. (2004). Evidence for a new conceptualization of semantic representation in the left and right cerebral hemispheres. *Cortex*, 40(3), 467–478.
- 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.
- Dollaghan, C. (1985). Child meets word: "Fast mapping" in preschool children. *Journal of Speech and Hearing Research*, 28(3), 449–454.
- Dumay, N., & Gaskell, M. G. (2007). Sleep-associated changes in the mental representation of spoken words. *Psychological Science*, 18(1), 35–39.
- Duzel, E., Yonelinas, A. P., Mangun, G. R., Heinze, H.-J., & Tulving, E. (1997). Event-related brain potential correlates of two states of conscious awareness in memory. *Proceedings of the National Academy of Sciences*, 94(11), 5973–5978.
- Eisele, J. A., & Aram, D. M. (1993). Differential effects of early hemisphere damage on lexical comprehension and production. *Aphasiology*, 7(5), 513–523.
- Federmeier, K. D. (2007). Thinking ahead: The role and roots of prediction in language comprehension. *Psychophysiology*, 44(4), 491–505.
- Federmeier, K. D., & Kutas, M. (1999a). Right words and left words: Electrophysiological evidence for hemispheric differences in meaning processing. *Cognitive Brain Research*, 8(3), 373–392.
- Federmeier, K. D., & Kutas, M. (1999b). A rose by any other name: Long-term memory structure and sentence processing. *Journal of Memory and Language*, 41(4), 469–495.
- Federmeier, K. D., Mai, H., & Kutas, M. (2005). Both sides get the point: Hemispheric sensitivities to sentential constraint. *Memory & Cognition*, 33, 871–886.
- Federmeier, K. D., Wlotko, E. W., & Meyer, A. M. (2008). What's 'right' in language comprehension: Event-related potentials reveal right hemisphere language capabilities. *Language and Linguistics Compass*, 2(1), 1–17.
- Friedrich, M., & Friederici, A. D. (2008). Neurophysiological correlates of online word learning in 14-month-old infants. *NeuroReport*, 19(18), 1757–1761. 1710.1097/WNR.1750b1013e328318f328014.
- Frishkoff, G. A., Perfetti, C. A., & Collins-Thompson, K. (2010). Lexical quality in the Brain: ERP evidence for robust word learning from context. *Developmental Neuropsychology*, 35(4), 376–403.
- Gaskell, M. G., & Dumay, N. (2003). Lexical competition and the acquisition of novel words. *Cognition*, 89(2), 105–132.
- Grönholm, P., Rinne, J. O., Vorobyev, V., & Laine, M. (2005). Naming of newly learned objects: A PET activation study. *Cognitive Brain Research*, 25(1), 359–371.
- Grose-Fifer, J., & Deacon, D. (2004). Priming by natural category membership in the left and right cerebral hemispheres. *Neuropsychologia*, 42(14), 1948–1960.
- Heibeck, T. H., & Markman, E. M. (1987). Word learning in children: An examination of fast mapping. *Child Development*, 58(4), 1021–1034.
- Huthison, K. A. (2003). Is semantic priming due to association strength or feature overlap? A microanalytic review. *Psychonomic Bulletin & Review*, 10(4), 785–813.
- Ince, E., & Christman, S. D. (2002). Semantic representations of word meanings by the cerebral hemispheres. *Brain and Language*, 80(3), 393–420.
- Jenkins, J. R., Stein, M. L., & Wysocki, K. (1984). Learning vocabulary through reading. *American Educational Research Journal*, 21(4), 767–787.
- Kandhadai, P., & Federmeier, K. D. (2010). Automatic and controlled aspects of lexical associative processing in the two cerebral hemispheres. *Psychophysiology*, 47(4), 774–785.
- Kiefer, M., Weisbrod, M., Kern, I., Maier, S., & Spitzer, M. (1998). Right hemisphere activation during indirect semantic priming: Evidence from event-related potentials. *Brain and Language*, 64, 377–408.
- Kiss, G. R., Armstrong, C., Milroy, R., & Piper, J. (1973). An associated thesaurus of English and its computer analysis. In: A. J. Aitken, R. Bailey, & N. Hamilton-Smith (Eds.), *The computer and literary studies*. Edinburgh: Edinburgh University Press.
- Koivisto, M. (1997). Time course of semantic activation in the cerebral hemispheres. *Neuropsychologia*, 35(4), 497–504.
- Koivisto, M., & Laine, M. (2000). Hemispheric asymmetries in activation and integration of categorical information. *Laterality*, 5(1), 1–21.
- Kutas, M., & Federmeier, K. D. (2001). 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(1), 621–647.
- Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207(4427), 203–205.
- Kutas, M., & Hillyard, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature*, 307(5947), 161–163.
- Lieven, E., Pine, J., & Baldwin, G. (1997). Lexically-based learning and early grammatical development. *Journal of Child Language*, 24(01), 187–219.
- Lucas, M. (2000). Semantic priming without association: A meta-analytic review. *Psychonomic Bulletin & Review*, 7(4), 618–630.
- Marsolek, C. J., Kosslyn, S. M., & Squire, L. R. (1992). Form-specific visual priming in the right cerebral hemisphere. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 18(3), 492–508.
- McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review*, 102, 3.
- McLaughlin, J., Osterhout, L., & Kim, A. (2004). Neural correlates of second-language word learning: Minimal instruction produces rapid change. *Nature Neuroscience*, 7(7), 703–704.

- McRae, K., deSa, V. R., & Seidenberg, M. S. (1997). On the nature and scope of featural representations of word meaning. *Journal of Experimental Psychology-General*, 126(2), 99–130.
- Mestres-Missé, A., Càmarà, E., Rodríguez-Fornells, A., Rotte, M., & Münte, T. F. (2008). Functional neuroanatomy of meaning acquisition from context. *Journal of Cognitive Neuroscience*, 20(12), 2153–2166.
- Mestres-Misse, A., Rodríguez-Fornells, A., & Münte, T. F. (2007). Watching the brain during meaning acquisition. *Cerebral Cortex*, bhl094.
- Meyer, D. E. (1970). On the representation and retrieval of stored semantic information. *Cognitive Psychology*, 1(3), 242–299.
- 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., 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., Plunkett, K., Prat, C., & Schafer, G. (2005). Watching the infant brain learn words: Effects of vocabulary size and experience. *Cognitive Development*, 20(1), 19–31.
- Nagy, W. E., Anderson, R. C., & Herman, P. A. (1987). Learning word meanings from context during normal reading. *American Educational Research Journal*, 24(2), 237–270.
- Nagy, W. E., Herman, P. A., & Anderson, R. C. (1985). Learning words from context. *Reading Research Quarterly*, 20(2), 233–253.
- Neely, J. H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In E. Derek Besner & E. Glyn W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 264–336). Erlbaum, Hillsdale, NJ, US.
- Nobre, A. C., & McCarthy, G. (1994). Language-related ERPs—Scalp distributions and modulation by word type and semantic priming. *Journal of Cognitive Neuroscience*, 6(3), 233–255.
- Ojima, S., Nakata, H., & Kakigi, R. (2005). An ERP study of second language learning after childhood: Effects of proficiency. *Journal of Cognitive Neuroscience*, 17(8), 1212–1228.
- Olichney, J. M., Van Petten, C., Paller, K. A., Salmon, D. P., Irarui, V. J., & Kutas, M. (2000). Word repetition in amnesia. *Brain*, 123(9), 1948–1963.
- Paulesu, E., Vallar, G., Berlinger, M., Signorini, M., Vitali, P., Burani, C., et al. (2009). Supercalifragilisticexpialidocious: How the brain learns words never heard before. *Neuroimage*, 45(4), 1368–1377.
- Perfetti, C. A., Wlotko, E. W., & Hart, L. A. (2005). Word learning and individual differences in word learning reflected in event-related potentials. *Journal of Experimental Psychology: Learning and Memory and Cognition*, 31(6), 1281–1292.
- Plaut, D. C., & Booth, J. R. (2000). Individual and developmental differences in semantic priming: Empirical and computational support for a single-mechanism account of lexical processing. *Psychological Review*, 107(4), 786–823.
- Rastle, K., Harrington, J., & Coltheart, M. (2002). 358,534 nonwords: The ARC nonword database. *Quarterly Journal of Experimental Psychology*, 55(A), 1339–1362.
- Rodríguez-Fornells, A., Cunillera, T., Mestres-Misse, A., & de Diego-Balaguer, R. (2009). Neurophysiological mechanisms involved in language learning in adults. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1536), 3711–3735.
- Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences*, 11(6), 251–257.
- Ruz, M., Madrid, E., Lupianez, J., & Tudela, P. (2003). High density ERP indices of conscious and unconscious semantic priming. *Cognitive Brain Research*, 17(3), 719–731.
- Shtyrov, Y. (2012). Neural bases of rapid word learning. *The Neuroscientist*, 18(4), 312–319.
- Shtyrov, Y., Nikulin, V. V., & Pulvermüller, F. (2010). Rapid cortical plasticity underlying novel word learning. *The Journal of Neuroscience*, 30(50), 16864–16867.
- Stein, M., Dierks, T., Brandeis, D., Wirth, M., Strik, W., & Koenig, T. (2006). Plasticity in the adult language system: A longitudinal electrophysiological study on second language learning. *NeuroImage*, 33(2), 774–783.
- Sternberg, R. J. (1987). Most vocabulary is learned from context. In: M. G. McKeown, & M. E. Curtis (Eds.), *The nature of vocabulary acquisition* (pp. 89–106). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Thal, D. J., Marchman, V. A., Stiles, J., Aram, D., Trauner, D., Nass, R., et al. (1991). Early lexical development in children with focal brain injury. *Brain & Language*, 40(4), 491–527.
- Tomasello, M. (1992). *First verbs: A case study of early grammatical development*. New York, NY: Cambridge University Press.
- Tompkins, C. A., Scharp, V. L., Meigh, K. M., & Fassbinder, W. (2008). Coarse coding and discourse comprehension in adults with right hemisphere brain damage. *Aphasiology*, 22(2).
- Torkildsen, J. v. K., Svangstu, J. M., Hansen, H. F., Smith, L., Simonsen, H. G., Moen, I., et al. (2008). Productive vocabulary size predicts event-related potential correlates of fast mapping in 20-month-olds. *Journal of Cognitive Neuroscience*, 20(7), 1266–1282.
- Travis, K. E., Leonard, M. K., Brown, T. T., Hagler, D. J., Curran, M., Dale, A. M., et al. (2011). Spatiotemporal neural dynamics of word understanding in 12- to 18-month-old-infants. *Cerebral Cortex*, 21(8), 1832–1839.
- Van Petten, C., & Kutas, M. (1990). Interactions between sentence context and word frequency in event-related brain potentials. *Memory & Cognition*, 18, 4.
- Van Petten, C., Kutas, M., Kluender, R., Mitchiner, M., & McIsaac, H. (1991). Fractionating the word repetition effect with event-related potentials. *Journal of Cognitive Neuroscience*, 3(2), 131–150.
- Weems, S. A., & Zaidel, E. (2005). Repetition priming within and between the two cerebral hemispheres. *Brain and Language*, 93(3), 298–307.
- Wilson, M. D. (1988). The MRC psycholinguistic database: Machine readable dictionary, version 2. *Behavioural Research Methods, Instruments and Computers*, 20(1), 6–11.
- Wlotko, E. W., & Federmeier, K. D. (2007). Finding the right word: Hemispheric asymmetries in the use of sentence context information. *Neuropsychologia*, 45(13), 3001–3014.
- Ye, Z., Mestres-Missé, A., Rodríguez-Fornells, A., & Münte, T. F. (2010). Two distinct neural networks support the mapping of meaning to a novel word. *Human Brain Mapping*, 32(7), 1081–1090.