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Once is Enough: N400 Indexes Semantic Integration of Novel Word Meanings from a Single Exposure in Context

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Abstract

We investigated the impact of contextual constraint on the integration of novel word meanings into semantic memory. Adults read strongly or weakly constraining sentences ending in known or unknown (novel) words as scalp-recorded electrical brain activity was recorded. Word knowledge was assessed via a lexical decision task in which recently seen known and unknown word sentence endings served as primes for semantically related, unrelated, and synonym/identical target words. As expected, N400 amplitudes to target words preceded by known word primes were reduced by prime-target relatedness. Critically, N400 amplitudes to targets preceded by novel primes also varied with prime-target relatedness, but only when they had initially appeared in highly constraining sentences. This demonstrates for the first time that fast-mapped word representations can develop strong associations with semantically related word meanings and reveals a rapid neural process that can integrate information about word meanings into the mental lexicon of young adults.

Although word learning is especially dramatic during early childhood, vocabularies continue to expand throughout the lifespan. Preliterate 5- or 6-year-old children are likely to know only 2,500–13,000 words, whereas it has been estimated that adults come to know between 40,000 and 150,000 words (Aitchinson, 2012; Beck & McKeown, 1991; Bloom, 2000; Pinker, 1994). Indeed, word learning continues throughout one's lifetime, and the large majority of vocabulary is acquired after early childhood (Anglin, 1993; Sternberg, 1987).

A substantial part of lexical acquisition research in children has investigated the cognitive mechanisms involved in explicit object and action name learning, and the degree to which these are specific to language (Bloom, 2000; Childers & Tomasello, 2002; Deak, 2000; Markman, 1992; Waxman & Booth, 2000). By contrast, lexical acquisition in adults has mostly been examined from the perspective of second language acquisition. This research has emphasized the cognitive and neural similarities (and differences) between word learning in an individual's first and second languages (Costa & Santesteban, 2004; Francis, 1999; Halsband, 2006; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Illes et al., 1999; Marian, Spivey, & Hirsch, 2003; Singleton, 1999; Tan et al., 2003). Although these areas of study have yielded important insights into how young children and/or bilingual adults learn words, the mode by which adults learn words in their native language is likely to have not only some important similarities but also some differences from that of young children and adult bilinguals. For example, growing electrophysiological evidence suggests that infants may process novel and known word meanings using neural mechanisms similar to those in adults (Friedrich & Friederici, 2004b, 2005; Mills, Plunkett, Prat, & Schafer, 2005; Torkildsen et al., 2008; Travis et al., 2011). At the same time, however, there are

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important differences in the ways that children and adults are exposed to words and how they learn them. For instance, studies of preliterate children often explore word learning in explicit training contexts, such as learning to name a novel object. Older children and adults, however, acquire words almost entirely via incidental learning, especially during reading (Jenkins, Stein, & Wysocki, 1984; Nagy, Anderson, & Herman, 1987; Nagy, Herman, & Anderson, 1985; Sternberg, 1987). Moreover, whereas young children typically map words to novel concepts for which they do not yet have a name (Markman & Wachtel, 1988), adults and school-age children more often learn nuanced or specialized meanings for concepts they already know and can otherwise refer to (e.g., jocund/happy) (Anglin, 1993). Given that adult word learning is so common but differs from that of child lexical learning in these ways, it is not surprising that this is increasingly a topic of interest to researchers.

The insights of developmental scientists studying lexical acquisition serve as a useful starting point as we begin to investigate adult lexical acquisition. This field has revealed that children are sensitive to various contextual cues in learning a word. The linguistic, physical, or social context in which a word occurs sets the stage for acquiring its meaning. This process may be incremental and extend across multiple instances spanning months or years after its initial exposure (Beck, McKeown, & Kucan, 2002; Bloom, 2000). Under the right conditions however, word learning can be remarkably fast. At times, only a single exposure to a novel word suffices for a learner, child or adult, to infer its likely meaning (Carey & Bartlett, 1978; Dollaghan, 1985; Heibeck & Markman, 1987) or to understand its appropriate usage in context (Borovsky, Kutas, & Elman, 2010), a process termed fast-mapping. This first encounter of a novel word is critical and lays the foundation for further elaboration of its meaning as well as proper usage.

Yet what exactly is learned in this initial exposure to a novel word? Much fast-mapping research has explored the formation of associations between an object and a label (Dollaghan, 1985; Golinkoff, Mervis, & Hirsh-Pasek, 1994; Houston-Price, Plunkett, & Harris, 2005; Markman, Wasow, & Hansen, 2003; Mervis & Bertrand, 1994; Werker, Cohen, Lloyd, Stager, & Casasola, 1998), or some physical feature and label (Carey & Bartlett, 1978; Heibeck & Markman, 1987). But our lexical knowledge is often far richer than simple associations between labels, physical objects and features. Word representations are complex and multi-faceted. The word-learner must remember a novel word's phonological form and, if literate, its orthographic representation; its meaning also must be appropriately situated within the local context and dynamic semantic landscape of the mental lexicon. For instance, when learning a novel bird's name, the learner might acquire information specific to the bird (e.g., its color, size, and feeding habits) and also link this knowledge to their existing knowledge of birds and other creatures (Collins & Loftus, 1975; Rosch & Mervis, 1975). Further, the proper contextual usage of the word must also be acquired, for example, how a novel noun coordinates with other words (such as verbs or modifiers) to be used appropriately in sentences and discourse. Very little, if any, of this understanding can be measured via novel object-label associations.

The surrounding linguistic context in which a word initially appears also is critically important in acquiring its meaning. The impact of context on lexical acquisition been largely explored by reading researchers who are interested in developing effective vocabulary instruction techniques for school-age children. This research has revealed that many contextual factors might influence incidental word learning, such as the size of semantic domain highlighted by the surrounding context (Shore & Kempe, 1999), genre of the text (e.g., expositive vs. narrative), density of conceptually difficult items in the context (Nagy et al., 1987), and amount of text surrounding a novel item (Swanborn & de Glopper, 1999). While this research has yielded important insights for instructors regarding general strategies for classroom vocabulary instruction, less work has rigorously examined how contextual factors might influence specific aspects of meaning acquisition and the mental time course of this representation. Instead, much of this work has assessed learner's knowledge via offline techniques that provide binary assessments of successful acquisition, such as identification of meaning in a multiple choice context or ability to generate a definition. These are useful measures of word learning in its final stages but are relatively reticent about earlier stages of learning, when the learner's knowledge may not be stable and/or robust enough to drive such overt behaviors. On-line techniques, including electrophysiological measures, offer the possibility of assessing more subtle "in progress" aspects of word learning. Understanding the various influences of context on the acquisition of specific aspects of word meaning could be tremendously helpful in identifying effective strategies for vocabulary instruction.

One unique contribution of the present study thus is its focus on these less-oft explored topics, specifically, how the contextual constraint in which novel words appear might impact the acquisition of one foundational aspect of lexical knowledge — namely, its relationship to other word meanings. It has been repeatedly demonstrated that children and adults can successfully fast-map novel label-object mappings using offline tasks of recognition and comprehension; less, however, is understood regarding the time course of this knowledge. To explore this aspect of word learning, we use an electrophysiological index of word recognition — the N400, described in greater detail below. As we will see, this measure appears to be sensitive to aspects of learning that are not always reflected in behavioral measures.

To summarize, the main goal of this research is to address a number of relatively unexplored questions: Exactly what kind of information is gained from an initial single exposure to a novel word in young adults? How much (if at all) does contextual constraint influence this representation? What are the brain indices of the time course of this rapid learning? Our studies examine the impact of sentential context on the representation of a novel word's meaning in semantic memory as indexed by the modulation of event-related brain potentials (ERPs) together with reaction times due to single trial word learning from sentence contexts. We ask whether a single exposure of a written word in a sentential context suffices to support semantic lexical priming, and whether this interacts with the nature (strength) of the sentential constraints for initial learning. To answer this question, we present novel words in sentence contexts that either strongly or weakly constrain their meaning and measure knowledge of word meaning via semantic priming using the N400 component of the ERP.

The N400 is a particularly sensitive measure of word learning. It is a negative going wave with a centroparietal maximum (for written words) that peaks approximately 400ms after the onset of any potentially meaningful stimulus (Kutas & Federmeier, 2000; Kutas & Hillyard, 1980). N400 amplitude has been found to decrease when a word is more expected or when features associated with its meaning are more easily integrated within its surrounding context (Kutas & Federmeier, 2000; Kutas & Hillyard, 1980; Kutas & Van Petten, 1994). Kutas and Hillyard (1980) recorded ERPs to sentence completions that were either congruent or incongruent with the context of the preceding sentence fragment. In a sentence such as "I drink my coffee with cream and *sugar,*" where the sentence ending is contextually congruent, the elicited N400 is reliably smaller than to sentences such as "I drank my coffee with cream and *dog,"* where the sentence completion is contextually incongruent.

One of the best predictors of N400 amplitude to written words in a sentence is the eliciting word's offline cloze probability (Kutas & Hillyard, 1984; Kutas, Lindamood, & Hillyard, 1984). Cloze probability is measured by calculating the probability that a particular word in a context is named on a given sentence completion task. For words with low cloze probabilities, the N400 is relatively large. N400 amplitude decreases as cloze probability increases. This correlation is consistent with the view that the N400 amplitude is related to a word's degree of expectancy and/or ease with which it may be integrated with its context. In addition, the N400 for orthographically legal and pronounceable nonwords (pseudo-words) is as large and sometimes larger than that for real words (Ziegler, Besson, Jacobs, Nazir, & Carr, 1997). The N400 is typically nonexistent for nonwords that do not have orthographically legal spellings or are unpronounceable (Bentin, 1987; Bentin, McCarthy, & Wood, 1985), although known acronyms (e.g., IBM) do elicit N400 activity (Laszlo & Federmeier, 2008). N400 amplitude is thus associated with a word's meaningfulness in a given context and the associated activation of information in semantic memory, ranging from very small in amplitude when a word is expected and thus already highly activated and accordingly very easily integrated into the ongoing context, to very large when it is contextually unexpected and thus more difficult to integrate, as in the case where the meaning of a possible word is unknown (Kutas & Federmeier, 2011).

A number of recent studies of adult first and second language learners suggest that the N400 can serve as a marker of word learning in both L1 and L2 (Borovsky et al., 2010; McLaughlin, Osterhout, & Kim, 2004; Mestres-Misse, Rodriguez-Fornells, & Munte, 2007; Ojima, Nakata, & Kakigi, 2005; Perfetti, Wlotko, & Hart, 2005; Stein et al., 2006). McLaughlin and colleagues, for example, compared N400 responses to French words in native French speakers and in (English as a first language) undergraduates learning French as a second language. They found that N400 amplitudes during a semantic priming lexical decision task using French words were modulated as learners became more proficient in French; further, after only a few months of instruction the N400s of college-aged learners in this task were indistinguishable from those of native speakers. These findings demonstrate not only that the brain may process word meanings acquired in childhood and adulthood similarly, but that lexical acquisition at least over extended training can be measured by modulations in neural activation.

In addition, L1 word learning studies have demonstrated even faster changes in brain activity due to word learning as indexed by the N400 component, ranging over the course of an hour (Perfetti et al., 2005) three exposures (Mestres-Missé, driguez-Fornells, & Münte, 2007), or even after a single trial (Borovsky et al., 2010). For example, Borovsky et al. (2010) examined how contextual constraint influences understanding of novel word usage after only a single presentation in young adults. Novel words were presented in a single highly or weakly constraining sentence context. The findings revealed that participants were able to incorporate significant information about the proper usage of novel words as the grammatical object of particular verbs after only a single instance, but only for novel words that initially appeared in strongly (and not weakly) constrained sentences.

Clearly, measuring understanding of word usage is only one of many potential ways in which to gauge acquisition of word knowledge. Alternatively, one might probe for explicit understanding of word meaning via definition generation. However, the majority of our vocabulary is not acquired explicitly (Nagy et al., 1985; Sternberg, 1987), and adults and children often have difficulty in producing word definitions. This suggests that this kind of knowledge may require extended learning.

It is, however, possible to probe for *implicit* understanding of partial word knowledge via tasks that index apprehension of a word's meaning in relation to other words. Part of our understanding of the words CAT, DOG, and CHAIR, for example, is that CAT and DOG have many similarities and features in common that are not shared by CHAIR. Adults can gain significant knowledge of this kind of relationship between word meanings with a few exposures in sentence contexts (Mestres-Missé et al., 2007).

One way to measure this kind of knowledge acquisition is to see whether the newly learned word can serve as an effective prime in a semantic priming task. An extensive body of research demonstrates that target words preceded, presumably primed, by an identical or semantically, associatively or categorically related word (e.g., doctor – NURSE, or doctor – DOCTOR) are associated with both faster response times (see Neely, 1991, for a review), as well as reduced N400 amplitudes (Anderson & Holcomb, 1995; Bentin et al., 1985; Brown & Hagoort, 1993; Deacon, Hewitt, Yang, & Nagata, 2000; Nobre & McCarthy, 1994; Ruz, Madrid, Lupianez, & Tudela, 2003) compared to target words preceded by words that are unrelated in meaning, or to nonwords (i.e., doctor – CHAIR, or doctor – FOOP). Such effects have been generally interpreted as reflecting the semantic functional organization of known words in the brain (Collins & Loftus, 1975; Hutchison, 2003; Lucas, 2000; McRae, deSa, & Seidenberg, 1997; Plaut & Booth, 2000). In this study, we examine whether newly encountered words also can serve as an effective prime after only a single exposure within a (weakly or strongly constraining) sentence. In this case, N400 amplitude reduction to a target word by a newly learned prime word will be taken as an index of encoding of the novel word's meaning into semantic memory. More specifically, we contrast how these same novel words prime target words that are identical, related, or unrelated in meaning, as inferred from their N400 amplitudes. We also explore whether context impacts the integration of novel word meaning into the mental lexicon by assessing the interaction between the priming effect and contextual constraint, with the expectation that words learned under high contextual constraint will make the most effective primes of word meaning.

METHODS

Participants

Twenty-four college students (13 F, 11 M) were given credit or paid $7/hour for their participation. Ages ranged between 18 and 30 (mean: 19.50). 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 11 participated but were not analyzed: five had excessive blinking or motion artifact, one because of equipment failure or experimenter error, and five reported a characteristic which disqualified them from analysis (four had significant second language exposure as a child, and one had nonnormal vision).

Materials

Stimuli consisted of 132 sentence pairs selected from Federmeier and Kutas (1999) and 528 word pairs selected to correspond with 132 sentence final words. Both are described in detail below:

Sentences—Sixty-six high constraint and 66 low constraint sentence pairs were selected from Federmeier & Kutas (1999), who had extensively normed them. The two sentences were designed such that together they established an expectation for a target word meaning, which was presented as the last word of the second sentence. 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 a median split of results of an offline cloze-procedure, as reported by Federmeier and Kutas (1999). These authors reported that the cloze probabilities for the high constraint sentences had ranged between 0.784 and 1, with an average value of 0.896 (and median of 0.904), while the cloze probability of the low constraint sentences ranged between 0.17 and 0.784, with an average value of 0.588 (median = 0.608). Sentence-final words thus were either plausible and expected known word sentence completions as in Federmeier and Kutas (1999), or unknown pseudo-words. There were 33 sentences in each of four main conditions: 1) Known word / High Constraint, 2) Unknown word / High Constraint, 3) Known word / Low Constraint, and 4) Unknown word / Low Constraint. Sentences were counterbalanced such that each High and Low constraint sentence pair appeared with both a Known and Unknown ending equally across all versions of the study, although not repeated within a subject. Known word target items consisted of words in 66 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. Table 1a includes examples of sentence stimuli.

Word-Pairs—Five hundred and twenty-eight word pairs were constructed for the study, consisting of a prime followed by a target word presented one stimulus at a time. Since repetition is known to diminish N400 amplitudes (Besson, Kutas, & Van Petten, 1992; Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991), and it is unclear whether or not repetition and constraint might interact, 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 amplitude of interest would thus be elicited by previously unseen real word targets (printed in all caps) in three conditions: 1) Synonym/Identical meaning (Syn/ID: rabbit-RABBIT), 2) Related (Rel: rabbit-MOUSE), and 3) Unrelated (Unrel: rabbit-RIBBON). Unrelated and Related word pairs were selected to be as closely matched as possible to the other target conditions in word frequency [$F(2, 353) = 1.0860$, $p = 0.3387$)], 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 as well. Targets in each condition did not differ as a function of constraint in frequency [Syn/ID: $|t| < 1$, Rel: $|t| < 1$, Unrel: $t(130) = 1.057$, $p = 0.2924$], length [Syn/ID: $t(130)=-1.45$, $p = 0.148$, Rel: $|t| < 1$, Unrel: $t(130)=-1.269$, $p = 0.2067$], number of syllables [Syn/ID: $|t| < 1$, Rel: $|t| < 1$, Unrel: $|t| < 1$], and number of phonemes [Syn/ID: $t(130)=-1.36$, $p=0.1775$, Rel: $|t| < 1$, 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 the Unknown word primes, Rel, Unrel, and Syn/ID were determined by the implied meaning of the sentence context in which the Unknown word had recently appeared.

An equal number of Nonword targets (pronounceable pseudo-words) were also constructed so that the proportion of “Yes” and “No” lexical decision responses were equivalent. Nonwords were selected using the ARC Nonword database (Rastle, Harrington, & Coltheart, 2002) and were selected to be pronounceable, conform to English phonotactics, and contain between four and seven letters. It is important to note that these “Nonwords” did not appear in the sentence contexts, unlike the pseudo-words presented in the Unknown word condition, and thus it would be reasonable to expect that participants would provide a “No” lexical decision response when they appeared.

In any one version, participants saw each Known and Unknown prime paired with two out of three possible Known word targets and two Nonword targets. The proportion of targets in each condition is as follows: Nonwords = 1/2, Syn/ID = 1/6, Rel = 1/6, Unrel 1/6. Versions were counterbalanced such that each Known and Unknown prime was matched=with the targets with equal frequency across versions. Table 1b includes examples of word pairs in the study.

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Procedure

Participants were tested in a single experimental session conducted in a soundproof, 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 presented in Figure 1.

In the sentence comprehension task, participants were instructed to read the sentence pairs for comprehension and to do their best to understand the sentence and words even when “nonsense” words appeared on the screen. The first sentence in each pair was presented in its entirety on the monitor, and participants were instructed to press a button to indicate that they had completed reading this sentence and were ready for the second. The second sentence was preceded by a set of crosses (500 ms duration with a stimulus-onset-asynchrony varying randomly between 300 and 800 ms) to orient the participant toward 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 each word that appeared on the screen and to indicate with a button press whether or not the target item (in capital letters) was a real word. Participants viewed two sets of prime/target pairs and were given a 2500 ms offset period to blink between pairs. Prime pair onsets were preceded by a set of fixation crosses that were randomly presented for 200–500 ms. Immediately following the fixation cross, a prime word appeared for 200 ms followed by an offset of 300 ms, by the target word presentation for 200 ms, and offset of 800 ms. Participants provided a lexical decision response as quickly as possible after the presentation of each target word.

Sentence comprehension and priming tasks were interleaved as follows. Participants read 12 sentence pairs and then completed the priming task consisting of 48 pairs, with primes being selected four times in random order from the 12 sentence endings that had just been read. Sentences were presented in this interleaved arrangement rather than having participants complete a priming task for all words at the end of the study for two reasons. First, we wanted to minimize potential differences due to recency of exposure by presenting the priming task for all words with a similar delay interval between presentation in the sentence context and the probe in priming task. Second, we were concerned that the large number of novel words presented in sentence contexts across the study (66) could potentially weaken any potential priming effects, especially for novel words that appeared at the beginning of the study. On a related note, we chose not to present the priming task immediately after each sentence in order to prevent explicit word learning and priming strategies, and to test integration of meaning after a delay (rather than immediately, as in prior work (Borovsky et al., 2010). After each sentence/priming set, participants were given a break before beginning a new block of sentences. The entire experiment consisted of 11 blocks of sentence/prime sets.

At the end of the study, participants were asked to complete an old/new memory questionnaire including 50 sentences that had appeared in the study and 50 sentences that had not. Participants were not told about this recognition memory test the beginning of the experiment; they were asked to indicate which sentences had appeared during the study, and which had not. This test was given to ensure that participants had sufficiently attended to the sentences during the study.

Electrophysiological recording

Scalp potentials were continuously recorded from 26 geodesically arranged sites using an ElectroCap with tin electrodes. Electrodes were placed at equal distances across the scalp, with positions and labels shown in Figure 2. A left mastoid reference was used. Potentials were digitized at a sampling rate of 250 Hz and hardware bandpass filter of 0.1-100Hz with Grass Amplifiers. Impedances were kept below 5 kΩ. The ERPs were stimulus-locked averages consisting of a 100-ms baseline and a 920 ms post-stimulus interval.

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 off-line 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 for the target words in the four learning conditions (Known/High, Known/Low, Unknown/High, and Unknown/Low) as well as to targets in all priming conditions (Syn/ID, Rel, and Unrel targets for each of the four main conditions Known/High, Known/Low, Unknown/High, and Unknown/Low) after subtraction of the 100 ms prestimulus baseline.

RESULTS

Behavioral performance

During the task, participants made lexical decisions for words that were identical, related, or unrelated in meaning to a prime word (known or unknown). Mean accuracy scores on this task are shown in Table 2. Since accuracy was near ceiling, with the lowest accuracy in any single condition being 93%, we did not statistically analyze effects of accuracy. Mean reaction times are also shown in Table 2 and Figure 3. A three-factor 2×2×3 repeated measures ANOVA was carried out with factors of Word Type (Unknown and Known) x Constraint (High and Low) x Prime relationship (Syn/ID, Rel and Unrel), with a by-subjects [F_1] and by-items [F_2] analyses. A main effect of the Prime relationship was found [$F_1(2, 46) = 85.49$, $p < 0.0001$, $F_2(2,260) = 14.20$, $p < 0.0001$], with post-hoc Tukey tests, revealing that this effect was driven by faster responses to Syn/ID targets than every other condition. No overall difference was found between Rel and Unrel conditions. A main effect of Word Type in the by-subjects analysis [$F_1(1, 23) = 11.94$, $p = 0.002$] was driven by faster responses to targets preceded by Known compared to Unknown words. However, an effect of Word Type was not found in the by-items analysis [$F_2(1,130) = 1.42$, $p = 0.236$]. An interaction of Prime relationship x Word Type was also observed [$F_1(2,46) = 29.20$, $p < 0.0001$, $F_2(2,260) = 3.38$, $p = 0.036$]. Follow-up Tukey tests revealed that this interaction was driven by targets that were preceded by Known/Syn/ID words eliciting faster responses than words in any other condition. No other significant two- or three-way interactions were observed. Although no significant three-way interaction was observed, pairwise t-test comparisons were carried out to examine the relationships between Syn/ID, Rel and Unrel targets in each of the four context conditions: Known/High, Unknown/High, Known/Low, and Unknown/Low. The results of these t-tests analyses are summarized in Table 3. These analyses revealed that targets preceded by Known/High and Known/Low word primes elicited faster reaction times when preceded by a Syn/ID prime, compared to a Rel or Unrel word. By contrast, targets preceded by Unknown words did not elicit reliable RT priming effects in any condition.

ERP data: N400 amplitude

Context sentence endings—We analyzed artifact-free ERP responses to sentence final target words in four conditions: Known/High, Known/Low, Unknown/High and Unknown/

Low. ERPs to sentence final endings are shown in Figure 4. N400 mean amplitude was measured between 250-500ms post final word onset at four centro-parietal electrode sites (RMCe, LMCe, MiCe, and MiPa) where N400 effects are typically largest. A two-factor repeated measures ANOVA with factors of Word Type (Known and Unknown) and Constraint (High and Low) revealed an effect of Word Type [$F(1,23) = 28.85$, $p < .0001$] with Known word endings eliciting smaller N400s than Unknown word endings. No other main or interaction effects were observed.

Priming task—Grand average ERPs to target words in the four main prime word conditions are shown in Figures 5 and 6 at all electrode sites and in Figure 7 at a single medial central electrode. As can be seen from Figure 7, an effect of Target type is seen via modulation of the negative going peak from 250–500ms (N400) in all Prime conditions, except for Unknown/Low words. N400 mean amplitude was measured between 250 and 500ms post target word onset at four centro-parietal electrode sites (RMCe, LMCe, MiCe, MiPa) where N400 effects are typically largest; these values are shown in Figure 8. A three-factor repeated measures ANOVA was conducted with factors of Word Type (Known or Unknown), Constraint (High or Low) and Prime relationship (Syn/ID, Rel, Unrel), using Greenhouse-Geisser univariate epsilon values.

This analysis revealed significant effects of Word Type [$F(1,23) = 5.50$, $p = 0.02$], with Unknown words eliciting larger N400 amplitudes, and Prime relationship = [$F(1.8922, 43.522) = 32.44$, $p < 0.0001$], with Syn/ID targets eliciting smaller N400 amplitudes, but no main effect of Constraint [$F(1,23) < 1$]. There was also an interaction of Constraint x Prime relationship [$F(1,23) = 6.29$, $p = 0.0196$], but no other two- or three-way interactions were reliable. Preplanned pairwise repeated measures ANOVA comparisons were then conducted to compare mean N400 amplitude between Rel, Unrel and Syn/ID targets in each of the four main Prime relationship conditions. As can be seen from Table 4, significant priming effects were observed in all priming conditions, except for Unknown prime words that initially appeared in Low constraint contexts. It should be noted that this pattern of N400 effects differ from the behavioral priming outcome Table 3, where there was no evidence of priming for Unknown items, and Known items did not show differences between related and unrelated items.

ERP Data: N400 distribution—The amplitude analyses conducted above were done with a limited set of electrodes over scalp sites where N400 effects are typically largest. To check that N400 effects did not differ in their scalp topography as a function of the experimental conditions, we conducted additional analyses on sentence final words in the sentences and target words in the priming task using a larger set of electrodes. In both analyses, the N400 was measured in the typical 250–500ms post word onset time window across 16 electrodes classified according to their position on the scalp. These distributional factors were Hemisphere (Right or Left), Anteriority (Prefrontal, Frontal, Central, or Occipital), Laterality (Medial or Lateral). The electrodes used in this analysis were LLPf, RLPf, LMPf, RMPf, LLFr, RLFr, LMFr, RMFr, LLTe, RLTe, LMCe, RMCe, LLOc, RLOc, LMOc, RMOc (see Federmeier, Mai, & Kutas, 2005). Below, the analyses for the sentence final words and then primes are reported.

Context Sentences—A repeated measures ANOVA was conducted with experimental factors of Word Type (Known and Unknown) x Constraint (High and Low), and distributional electrode factors of Hemisphere (Right and Left), Anteriority (Prefrontal, Frontal, Central, and Occipital) and Laterality (Medial and Lateral). Main effects were observed for the following factors: Word Type [$F(1,23) = 31.92$, $p < 0.0001$], Anteriority [$F(3,69) = 17.20$, $p < 0.0001$], and Laterality [$F(1,23) = 103.71$, $p < 0.0001$]. Interactions of distributional factors included: Hemisphere x Anteriority [$F(3,66) = 6.27$, $p = 0.0008$], and

Anteriority x Laterality [F(3,69) = 33.19, p < 0.0001], and Hemisphere x Anteriority x Laterality [F(3,69) = 9.65, p < 0.0001], driven by a tendency of the N400 to be more negative over left occipital sites and larger over lateral sites at all regions except pre-frontally. Word Type also interacted with a number of distributional factors. Interactions of Word Type x Hemisphere [F(1,23) = 4.38, p = 0.048], Word Type x Laterality [F(1,23) = 27.94, p = 0.0004], Word Type x Anteriority p < 0.0001], Word Type x Anteriority [F(3,69) = 7.01, Laterality [F(3,69) = 3.83, p = 0.013] and Word Type x Hemisphere x Laterality [F(1,23) = 8.64, p = 0.007] were driven by a tendency for novel word N400 amplitudes to be larger relative to known words, and for these amplitude differences to be largest in the left hemisphere and in prefrontal and medial sites.

Priming task—A repeated measures ANOVA was conducted with experimental factors ofWord Type (Known and Unknown) x Constraint (High and Low), and Prime Relationship (Syn/ID, Rel, and Unrel), and distributional electrode factors of Hemisphere (Right and Left), Anteriority (Prefrontal, Frontal, Central, and Occipital) and Laterality (Medial and Lateral). Main effects were observed for the following factors: Word Type [F(1,23) = 11.18, p < 0.0028], Prime [F(2,46) = 22.12, p < 0.0001], Anteriority [F(3,69) = 8.44, p < 0.0001], and Laterality [F(1,23) = 29.27, p < 0.0001]. A significant interaction of distributional factors Anteriority x Laterality [F(3,69) = 44.93, p < 0.0001] was driven by a tendency for the N400 to be larger over lateral sites except over prefrontal electrodes. Other interactions observed were Word Type x Prime [F(2,46) = 8.15, p < 0.0001], Constraint x Prime [F(2,46) = 3.70, p = 0.032], Word Type x Anteriority [F(3,69) = 18.67, p < 0.0001], Prime x Anteriority [F(6,138) = 6.86, p < 0.0001], Prime x Laterality [F(2,46) = 22.13, p < 0.0001], Hemisphere x Prime [F(2,26) = 7.66, p < 0.0013], Constraint x Anteriority x Prime [F(6,138) = 2.65, p = 0.019], Constraint x Laterality x Prime [F(2,46) = 5.36, p < 0.008], and Hemisphere x Laterality x Prime [F(2,46) = 7.07, p = 0.002]. No four-, five- or six-way interactions was significant between the three experimental factors together (Word Type x Constraint x Prime) and any individual or combination of distributional factors.

Relationship between sentence context and priming targets—In principle, the differential priming effects as a function of initial constraint for Unknown words could be driven by potentially stronger semantic relationships between the prime targets and the High (compared to Low) constraint sentence contexts rather than by differences in the encoded Unknown word representations per se. For example, it is arguable that High constraint sentence (such as, Tina lined up where she thought the nail should go. When she was satisfied, she asked Bruce to hand her the VORN) might contain a greater number of words that are lexically associated to the priming targets (HAMMER and SCREWDRIVER in this case) than Low constraint contexts (such as, Pablo wanted to cut the lumber he had bought to make some shelves. He asked his neighbor if he could borrow her THANT, with subsequent prime targets of SAW and AWL*)*. Thus, it is possible that upon subsequent priming, it could be that the initial sentence context itself, and not the inferred meaning of the word that could lead to the differential effect of constraint on novel word priming due to the association between the initial sentence context and the prime target. To explore this possibility, we compared the similarity of the High and Low sentence context words with that of the Syn/ID, Rel, and Unrel prime targets using latent semantic analysis (LSA; Landauer, Foltz, & Laham, 1998). LSA is a mathematical technique that characterizes the semantic meaning of words and texts by similarities in their usage across textual contexts. This measure yields vector values for words and texts, which can be compared by computing the cosine of their angle. The resulting cosine similarity values have been shown to correlate highly with human judgments of meaning similarity (e.g., Landauer & Dumais, 1997). Using this technique, we analyzed the cosine of vector values obtained via LSA for primes and targets using a 2 × 3 ANOVA with factors of Constraint (High and Low) and

Prime Relatedness (Syn/Id, Rel and Unrel). Average LSA values in each condition are reported in Table 5. This analysis revealed a main effect of Relatedness [$F(2,383) = 15.72$, $p < 0.0001$], with post-hoc Tukey tests indicating that Syn/ID targets had higher overlap with sentence context words than either Rel or UnRel targets. However, neither a main effect nor an interaction with Constraint was observed. Thus, differential relationships between the sentence context and priming targets alone cannot explain the priming differences between Unknown/High and Unknown/Low conditions.

DISCUSSION

In this study, we set out to examine the impact of contextual constraint (high versus low) on the first moments of word learning (fast-mapping) in young adults by assessing its efficacy as a prime in a semantic priming lexical decision task. Our aim was to determine whether the degree of sentential constraint influences the initial encoding and integration of a novel word's meaning into the existing mental lexicon and the semantic network of word meanings across that lexicon. This question was motivated by a growing body of research on rapid neural changes associated with word learning in adults' native language. Recent findings show that electrophysiological brain measurements can index acquisition of lexico-semantic relationships between novel and known words after several presentations in increasingly constraining contexts (Mestres-Misse et al., 2007), can reflect sophisticated knowledge of word usage after only a single presentation, and can demonstrate an interaction between strength of initial learning context and subsequent novel word usage online (Borovsky et al., 2010). Building on these findings, we sought to examine the depth of semantic knowledge gained in a single exposure from context using ERP methodology. In previous research with similar materials, we probed immediate and overt knowledge of word usage. The current study extends our understanding of the nature of fast-mapped word knowledge by examining a delayed, implicit measure of word acquisition (semantic priming) via a lexical decision task. We examined both behavioral and ERP responses as young adult participants performed a lexical decision task in which known and newly learned (unknown) words that had recently appeared in strongly or weakly sentence contexts served as primes for known words that were either related, unrelated, or were identical in meaning to or synonyms of the prime word.

We note first that the behavioral lexical decision times did not reveal any reliable evidence of priming between novel word meanings and their related or synonymous targets (Table 3). This result alone might suggest that no word meaning learning occurred, regardless of how informative or constraining the sentential learning context might have been. However, we found no significant behavioral priming effects for Related versus Unrelated targets preceded by Known word primes either (although we did find significant priming in the Synonym/ID condition).

The ERP data, by contrast, tell a very different story (Table 4). Unknown word primes, like known word primes, did lead to a reduction in the N400 amplitude of semantically related target words. Semantic relatedness between an Unknown prime and a real word target could only have been inferred from the sentence context in which the Unknown word had recently been introduced for the first time. Importantly, this N400 amplitude reduction was reliable only for Unknown words that had initially appeared in a strongly (and not weakly) constraining context. As expected, Known word primes produced significant N400 priming effects: N400s for targets were smaller when preceded by words that were identical or related in meaning, relative to unrelated primes. Moreover, the priming effect was stronger for Known words that appeared in High vs. Low constraint contexts. The N400 differences between Related and Unrelated conditions might in principle be due to stimulus differences across conditions. It is unlikely, however, given that the stimuli were controlled for many of the factors known to affect N400, including, frequency, length, concreteness, and imageability.

To assess possible differences in "semantic distance" between the Known/High and Known/Low prime/target pairs, we computed the "semantic similarity" of these pairs using two methods: Latent Semantic Analysis (described earlier), and the McRae semantic feature production norms (McRae, Cree, Seidenberg, & McNorgan, 2005). Both of these measures failed to reveal differences in semantic similarity between the priming pairs, suggesting that the "semantic distance" or "relatedness" of these pairs did not differ across conditions, and thus could not drive the observed differences between them. Although the impact of sentential constraint on immediate semantic activation has been well studied, little is known about longer term effects that might arise from sentential constraint on Known word processing, calling for further study. These differences in Known word N400 priming effects are relatively minor, however, when compared to the constraint differences that appear for Unknown words. The N400 priming effects observed for Unknown/High words are not evident in the concomitant lexical decision times.

Such dissociations between N400 amplitudes and RT measures are not uncommon in the literature. For instance, a number of studies of indirect priming (cat – CHEESE via mouse) find N400 priming effects but do not find reliable RT effects (Chwilla, Kolk, & Mulder, 2000; Kiefer, Weisbrod, Kern, Maier, & Spitzer, 1998). Indirect priming effects tend to be more subtle than directly related priming (cat – DOG), and may more closely resemble single trial novel word learning. Moreover, some investigations of certain direct semantic priming tasks (like letter search) reveal N400 effects in the absence of RT effects (Heil, Rolke, & Pecchinenda, 2004; Küper & Heil, 2009). A dissociation between N400 and RT measures also exists in a study of word learning in a second language (McLaughlin et al., 2004). In sum, there are numerous instances in which electrophysiological and behavioral measurements of semantic priming and word learning are both present or are singly present; dissociations seem to be more likely in tasks where priming effects may otherwise be small. This seems like a possible case in the current study, where we fail to find a behavioral priming effect between related and unrelated known words (but not between identical and unrelated known words). It also suggests that there may be other tasks in which larger effects may be expected (such as in presenting words multiple times over several contexts), in which case a RT/N400 dissociation would be less likely.

Our ERP results indicate that the contextual constraint of a word's initial learning context leads to subsequent differences in access to and/or nature of that word's representation in the mental lexicon; novel words that had appeared in strongly constraining contexts led to modulations of the N400 as a function of prime-relatedness, while those that had appeared in weakly constraining contexts did not. These results suggest that the novel words experienced in these strongly (versus less) constrained contexts developed stronger links to semantically similar known word meanings. Moreover, according to the LSA results, these links are not due to a simple "reactivation" of the initial sentence context upon seeing the novel word. Rather, it seems that these ERP results are driven by an association between the novel word's (inferred) meaning and its relationship to other words in the lexicon. Further, the scalp distribution of ERP priming effects (i.e., their topographies) did not differ for novel versus known words, consistent with the view that novel words that had appeared in highly constraining contexts acted in their priming capacity like known words, that is, via similar neural and cognitive mechanisms to activate related concepts. These fast-mapped links suggest that a rapid neural mechanism indexed by the N400 component is involved in the encoding and integration of novel word meanings in semantic memory. To our knowledge, this kind of incorporation of novel word meaning into the mental lexicon of a young adult after a single exposure in context has not yet been demonstrated.

Despite this evidence for rapid semantic integration of novel word meaning, it is likely that there are limits to these nascent lexical representations. We suspect that these representations are fragile, and thus may not be effective after a week's time, or perhaps even a day. We examined the impact of context on the fast-mapped representation of word meaning after only a few minutes. Yet in normal learning contexts the meaning of new words are often incrementally reinforced and elaborated after multiple exposures across a variety of contexts (Nagy et al., 1985; Sternberg, 1987). These multiple exposures undoubtedly enrich the understanding of words and allow them to be remembered for longer durations (months, years, decades). We predict that words seen only once as in this study are likely to be forgotten without further reinforcement (Carey & Bartlett, 1978; Horst & Samuelson, 2008). Future research would be necessary to delineate the temporal and representational limits of fast mapped word meanings.

The strong constraint contexts in this study were developed to create an expectation for a single, familiar word (and thus word meaning) in the sentence final position. It could be that the expectation of this highly familiar and known word in the strong constraint contexts may have led adults to simply substitute or associate this meaning with the novel word. In fact, this could serve as a fundamental process by which adults learn novel words, who, unlike children, often learn novel words that highlight a particular facet of an already known word meaning (such as voluminous for big). Clearly, weak constraint contexts do not lend themselves to a single sentence final meaning, and thus would not be subject to this type of substitution mechanism.

This possible account raises an important question regarding how we might expect children to perform in similar tasks. A reasonable concern is that very young children might have some difficulty in learning word meaning solely from linguistic contexts. Even though our sentence contexts would be developmentally inappropriate for infants and toddlers, it is known that children learn much of their vocabulary from child-appropriate linguistic context (Sternberg, 1987). Indeed, by age 8, the majority of a child's vocabulary expansion is driven largely by exposure to a variety of written language materials (Anglin, 1993).

Yet another concern may be that children with especially small lexicons might not have a structured lexico-semantic framework in which to organize categorical relationships between words. However, the evidence suggests otherwise. Infants as young as 20 months have shown N400-like semantic priming effects (Torkildsen et al., 2006) similar to the type probed in adults in the current study. N400-like effects in picture-word congruency tasks also have also been observed in infants as young as 12–18 months (Friedrich & Friederici, 2005; Travis et al., 2011). Systematic and reliable modulations of N400 amplitudes to *known* wordsasafunction of meaningful relationships are found in young children. Research with infants has revealed N400 congruency effects to *novel* word-picture associations in 20 month (Torkildsen et al., 2008) and 14-month-old infants (Friedrich & Friederici, 2004a). Taken together, these results suggest that even very young children recognize lexico-semantic relations between words within categories, much like adults.

In sum, this foundational electrophysiological work in infants suggests that ERPs may be a suitable method to probe word learning in sentential contexts even in very young children. Indeed, ERP methods are well-suited to developmental investigation of word learning, as knowledge can be probed without an overt response. This methodology not only makes it possible to examine if a novel word has been successfully acquired, but also to examine what kind of knowledge has been learned. We are excited about the possibilities of adapting this paradigm and method to other hypotheses regarding lexical acquisition in children.

In summary, ours is the first study to reveal that adults can rapidly encode and integrate novel word meanings into their mental dictionaries after only a single exposure. Our results add to previous findings that the N400 component is sensitive to acquisition of word meanings after multiple exposures, and understanding of how a word can and cannot be used grammatically after only a single exposure in a highly constraining context. More generally, this paradigm offers a novel method to examine the impact of sentential context and constraint on word processing. With this study, we complement and supplement a growing body of evidence that the rapidly acquired information about novel words is detailed and sophisticated, including information about both its meaning and usage in sentence contexts. Further research is needed to extend these findings to other aspects of word meaning and knowledge, and to determine how long such information about a word's usage and meaning is retained and is effective.

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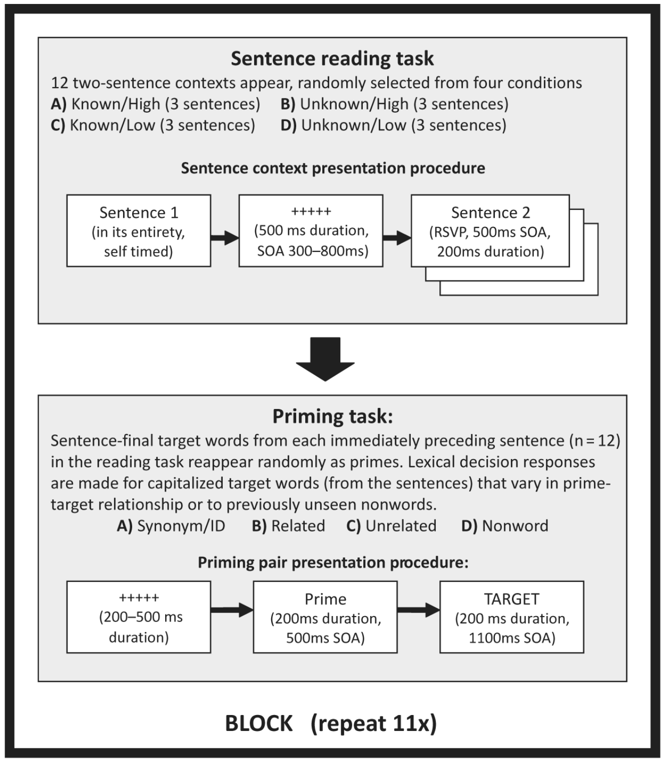

FIGURE 1.

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

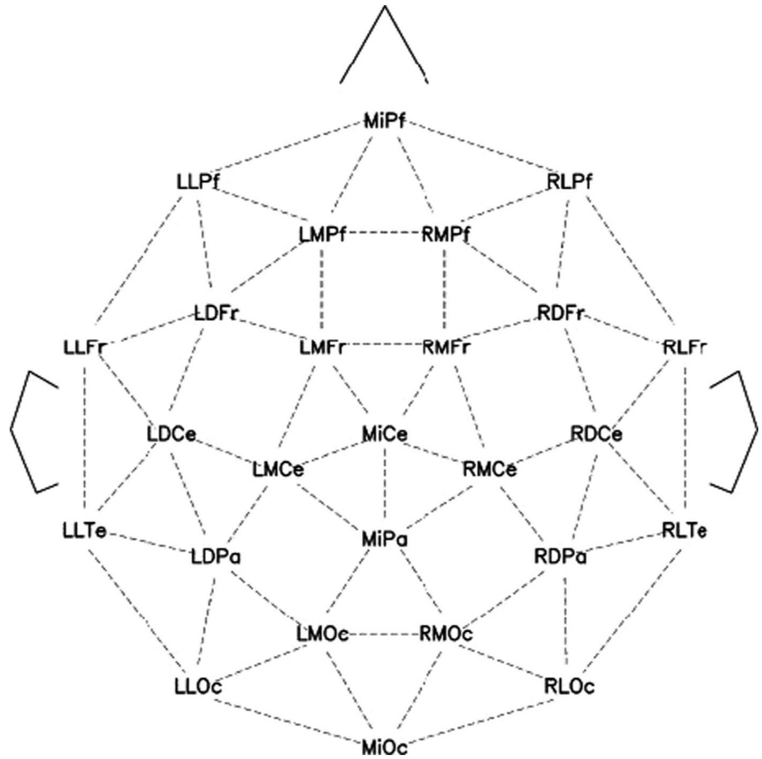

FIGURE 2.
iagram of the electrode positions and labels.

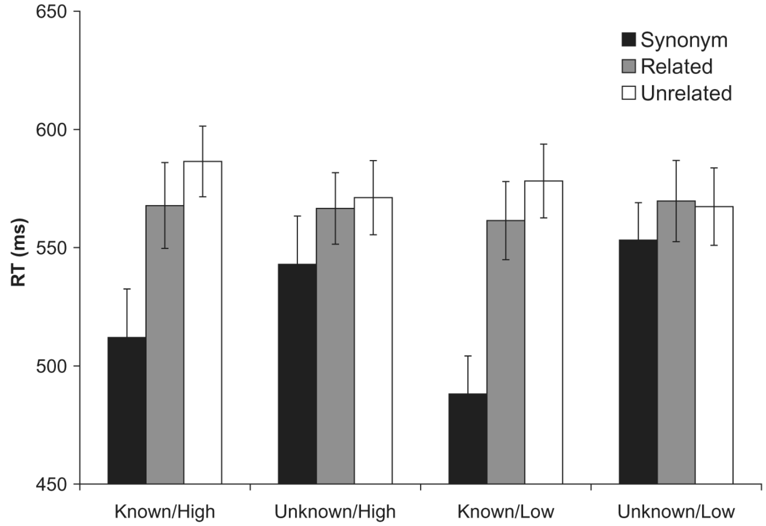

FIGURE 3.
ean reaction time to target items on priming task.

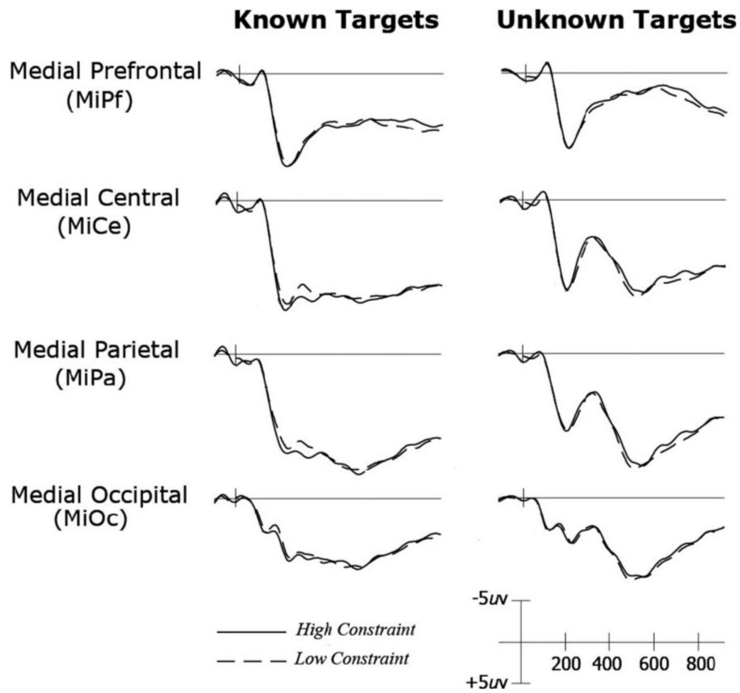

FIGURE 4.
rand average ERPs to known and unknown target words in context sentences at medial electrode sites.

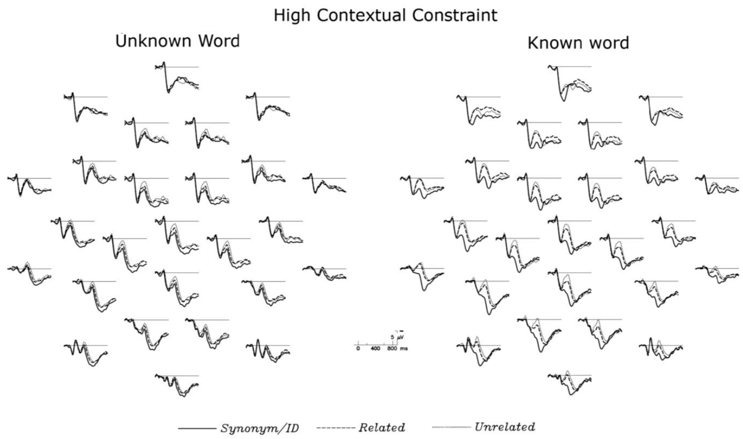

FIGURE 5.

rand average ERPs across all subjects and electrode sites for targets in the priming task that were initially preceded by Known and Unknown words that initially appeared in highly constraining sentence contexts.

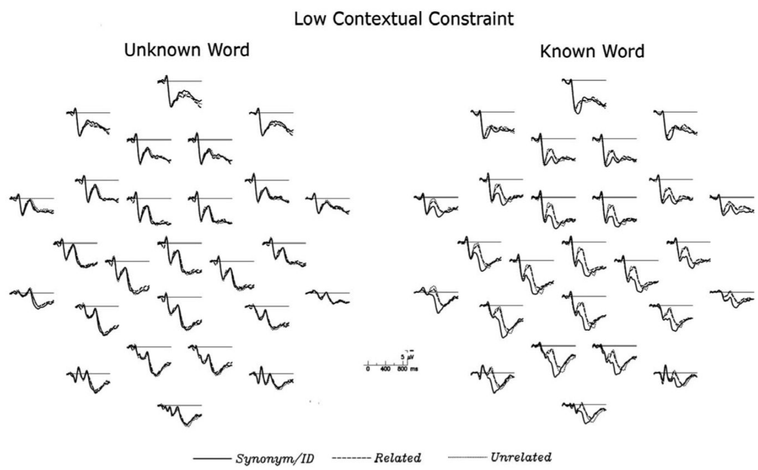

FIGURE 6.
rand average ERPs across all subjects and electrode sites for targets in the priming task that were initially preceded by Known and Unknown words that initially appeared in weakly constraining sentence contexts.

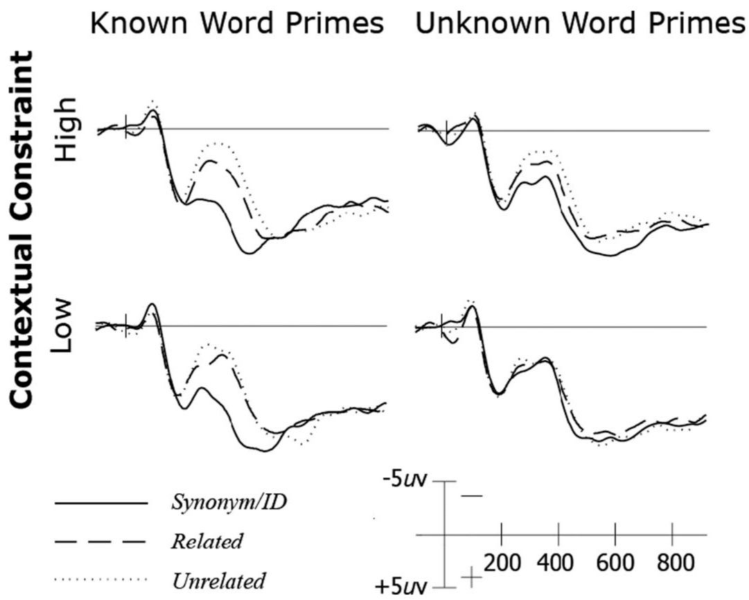

FIGURE 7.
rand average ERPs to target words in priming task at the vertex electrode (MiCE).

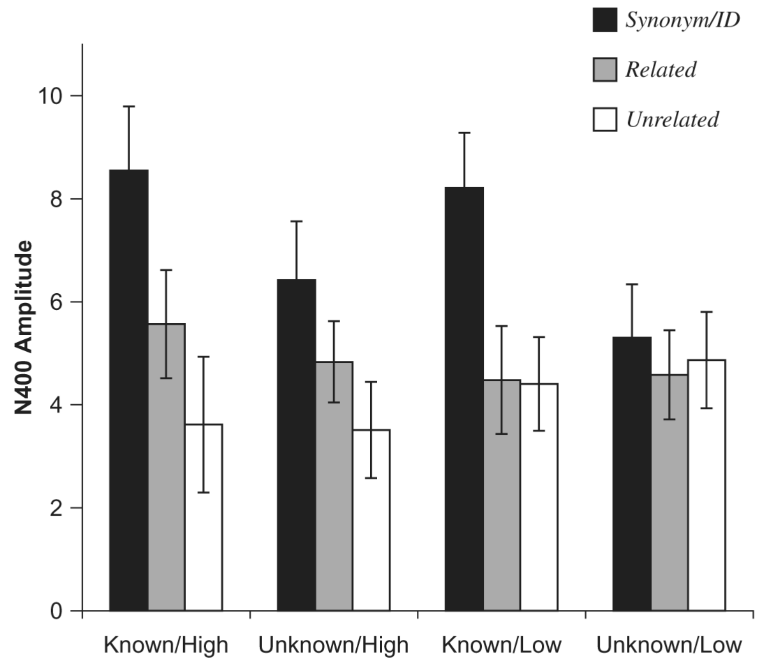

FIGURE 8.
400 Mean amplitude measured from 250-500ms averaged across four electrode sides, MiCE, RMCe, LMCe, MiPA for target words across four prime conditions. Since the N400 is a negative going wave, larger N400 amplitudes are represented by smaller values on this figure.

TABLE 1

Examples of sentences and word pairs in each condition

A) Context Sentences (Word Type/Context Constraint)

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	Related	Unrelated
Known/High	magazine-MAGAZINE	magazine - NOVEL	magazine- ACCIDENT
	hammer - HAMMER	hammer-SCREWDRIVER	hammer - LOCKER
Unknown/High	yerge – MAGAZINE	yerge – NOVEL	yerge- ACCIDENT
	vorn - HAMMER	vorn - SCREWDRIVER	hammer - LOCKER
Known/Low	book – BOOK	book – LETTER	book – ROAD
	saw - SAW	saw - AWL	saw - FACE
Unknown/Low	shus – BOOK	shus – LETTER	shus – ROAD
	thant - SAW	thant - AWL	thant – FACE

Note All word pairs were also paired with an equal number of previously unseen pseudoword (nonwords) targets, not depicted in this table. 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.

TABLE 2

Mean percentage of correct responses and mean reaction times (ms) for priming task in all conditions

	Known Word Primes		Unknown Word Primes	
	High Constraint	**Low Constraint**	**High Constraint**	**Low Constraint**
Percent correct				
Syn/ID	99 (0.6)	99 (1.9)	97 (6)	98 (2.1)
Rel	97 (2.4)	93 (4.1)	94 (4.3)	95 (3.5)
Unrel	93 (6.8)	96 (3.2)	95 (3.4)	94 (3.8)
Reaction time				
Syn/ID	512 (80)	488 (82)	543 (77)	553 (76)
Rel	568 (87)	561 (72)	567 (79)	570 (83)
Unrel	586 (79)	578 (75)	571 (75)	567 (79)

Note. Standard deviations are reported in parentheses.

TABLE 3

T-statistics from pairwise T-tests comparing mean RT to related, unrelated, and synonym/ID targets in four main prime conditions

		Syn/ID	Rel	Unrel
Known/High		Subjects:	Subjects:	Subjects:
	Syn/ID	–	2.65*	3.74**
	Rel	2.65*	–	ns
	Unrel	3.74**	ns	–
Known/Low				
	Syn/ID	–	2.46*	3.13**
	Rel	2.46*	–	ns
	Unrel	3.13**	ns	–
Unknown/High				
	Syn/ID	–	ns	ns
	Rel	ns	–	ns
	Unrel	ns	ns	–
Unknown/Low				
	Syn/ID	–	ns	ns
	Rel	ns	–	ns
	Unrel	ns	ns	–

*Asterisks (*) denote statistical significance at the following levels: $p < 0.05$,

**$p < 0.01$.

TABLE 4

F-values from pairwise ANOVAs comparing mean amplitude N400 to related, unrelated, and synonym/ID targets in four main prime conditions

		Syn/ID	Rel	Unrel
Known/High				
	Syn/ID	–	14.92 **	30.22 ***
	Rel	14.92 **	–	11.17 **
	Unrel	30.22 ***	11.17 **	–
Known/Low				
	Syn/ID	–	27.80 ***	23.69 ***
	Rel	27.80 ***	–	Ns
	Unrel	23.69 ***	ns	–
Unknown/High				
	Syn/ID	–	6.22 *	32.24 ***
	Rel	6.22 *	–	4.61 *
	Unrel	32.24 ***	4.61 *	–
Unknown/Low				
	Syn/ID	–	ns	ns
	Rel	ns	–	ns
	Unrel	ns	ns	–

*Asterisks (*) denote statistical significance at the following levels: $p < 0.05$,

**$p < 0.01$,

***$p < 0.0001$.

TABLE 5

LSA values between High and Low sentence contexts and prime targets

	Synonym/ID	Related	Unrelated
Constraint			
High	0.272 (0.012)	0.236 (0.012)	0.19 (0.012)
Low	0.258 (0.013)	0.207 (0.011)	0.201 (0.014)

Note Standard errors reported in parentheses.