Processing Visual Words With Numbers: Electrophysiological Evidence for Semantic Activation

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Abstract

Perea, Duñabeitia, and Carreiras (2008) found that LEET stimuli, formed by a mixture of digits and letters (e.g., "T4BL3" instead of "TABLE"), produced similar priming effects as regular words. This finding led them to conclude that LEET stimuli automatically activate lexical information. The present study examined whether semantic activation occurs for LEET stimuli using an electrophysiological measure called the N400 effect. The N400 effect, also known as mismatch negativity, reflects detection of a mismatch between a word and the current semantic context. This N400 effect can occur only if the LEET stimulus has been identified and processed semantically. Participants determined whether a stimulus (word or LEET) was related to a given category (e.g., "APPLE" or "4PPL3" belongs to the category "fruit" but "TABLE" or "T4BL3" does not). We found that LEET stimuli produced an N400 effect similar in magnitude to that for regular uppercase words, suggesting that LEET stimuli can access meaning in a similar manner to words presented in consistent uppercase letters.

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Humans possess the incredible ability to identify words irrespective of font type, size, or relative letter position (for examples, see e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005; Velan & Frost, 2007). Most models of visual word recognition attempt to explain these (and other) phenomena by considering multiple levels of activation, including orthographic, lexical, phonological, and semantic (e.g., Allen, Smith, Lien, Kaut, & Canfield, 2009; Balota, Yap, & Cortese, 2006; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart 1981). These models typically assume a continuous flow of information from recognizing orthographic form to retrieving meaning, either in a cascaded or parallel processing mode. Despite diverse assumptions proposed in variations of those models, they generally agree that visual word recognition is mediated by the perceptibility of words (see Lupker, 2005, for a review).

A study by Perea, Duñabeitia, and Carreiras (2008) demonstrated that visual word recognition is not disrupted by displaying words with characters sharing similar configural features with their constituted letters. They used LEET stimuli, where certain letters replaced by letter-like digits (e.g., the digit “3” for the letter “E”; “R34D1NG” instead of “READING”). They argued that if detecting the shape of individual letters is sufficient to produce lexical activation, then letter-like digits or letter-like symbols should produce lexical activation just like regular words. To test this claim, Perea et al. used a masked priming paradigm. They presented a forward mask (a row of #s) for 500 ms followed by a 50-ms prime in the center location. Immediately after the offset of the prime, the target appeared in the same location and remained on the screen until participants made a response. To reduce spatial overlap between prime and target, Perea et al. presented primes and targets in different font sizes (10-point Courier vs. 12-point Courier, respectively). Participants were to determine whether the target was a word (a lexical-decision task). In Experiment 1, the prime was either the same target word (e.g., “MATERIAL” for the target “MATERIAL”), corresponding LEET for that target (e.g., “M4T3R14L”), corresponding symbols (letter-like symbols; e.g., “MΔT€R!ΔL”), or control letters (replacing the original letters with other letters, randomly selected; e.g., “MOTURUOL” for the target “MATERIAL”).

Perea et al. (2008) found that response times (RTs) to the target word were significantly faster when they were primed by LEETs and symbols than when they were primed by the control letters (i.e., a priming effect). Most importantly, both LEETs and symbols produced similar mean RTs as the target word prime. They further found in Experiment 2 that both LEETs and symbols produced faster RT than their corresponding control conditions where other non-letter-like numbers and symbols, respectively, were used (e.g., “M6T2R76L” for the target “MATERIAL” in the control LEET condition; “M□T%R?□L” in the control symbol condition). They concluded that “it is visual similarity rather than the status of the leet digits as numbers that seems to be responsible for the leet priming effect” (p. 239).

Perea et al.’s (2008) findings with the masked priming paradigm seem to support the conclusion that, in the absence of a top-down context, letter-like digits (and symbols) embedded in a word are sufficient to trigger lexical activation. Nevertheless, some studies have suggested that priming effects result from prelexical processing (i.e., affecting stages prior to lexical activation; see Hutchison, Neely, Neill, & Walker, 2004; Masson & Isaak, 1999). In other words, the similarity of visual shape of LEET stimuli to actual letters may have affected only orthographic but not lexical processing of the target word. Evidence favoring the sublexical account mainly comes from the finding of similar repetition priming effects for words and nonwords in the lexical decision task, even though nonwords should not benefit from lexical processing of primes (e.g., Masson & Isaak, 1999). Thus, the advantage for LEET stimuli over the nonword control primes (e.g., "M4T3R14L" vs. "MOTURUOL" for the target word "MATERIAL") in Perea et al. (2008) could arise merely from less visual impairment in the LEET condition comparing to other stimulus conditions (e.g., Davis & Lupker, 2006; Horemans & Schiller, 2004; see Forster, 1998, for a review).

Because the priming effect with LEET stimuli observed in Perea et al. (2008) cannot be unambiguously attributed to lexical activation, this highlights a need for converging evidence. Because it is unclear whether priming results from lexical activation, we instead examined semantic activation of LEET stimuli using a category judgment task – determining whether a single stimulus (either a word or LEET stimulus) is related or unrelated to the category provided prior to that block. It has been suggested that semantic relatedness judgments, regardless of whether they are related or unrelated, are a result of lexical activation (e.g., Besner, Smith, & MacLeod, 1999). Accordingly, if we find any evidence of semantic activation, then we can infer the occurrence of lexical activation.

In addition to examining semantic activation using behavioral data (e.g., RT), we used event-related potential (ERP) measures. The ERPs provide online, continuous measures of meaning extraction and often reveal evidence of deeper processing than is apparent in behavioral data. For instance, Heil, Rolke, and Peccinenda (2004) found a modulation of ERP amplitudes by semantic relatedness of prime and probe words even when there was no semantic priming effect in RT (e.g., Rolke, Heil, Streb, & Hennighausen, 2001; see also Vogel, Luck, & Shapiro, 1998, for an example of ERPs elicited by semantic activation even when participants could not report targets in the attentional blink task). By examining the ERP components associated with semantic activation, it is possible to determine whether LEET stimuli trigger semantic activation just like regular words.

We used the N400 component, a negative-going brain potential that occurs around 400 ms after the onset of potentially meaningful stimuli (e.g., words). This component is also called *mismatch negativity* because it is known to be elicited when a person notices a stimulus that is incongruent with the current semantic context (see Kutas & Van Petten, 1988, for a review). For instance, after one sees the word "SPORTS", the word "APPLE" (unrelated) would elicit a much large negative ERP comparing to the word "TENNIS" (related) during 400-600 ms after word onset. Therefore, the *N400 effect* can be quantified as the average difference in brain potentials between words that are related and unrelated to the current semantic context (*N400 effect = unrelated word ERPs – related word ERPs*).

The critical point is that the N400 effect can be used as an indicator that a person has extracted word meaning. That is, the N400 effect occurs only when participants detect a semantic mismatch, indicating processing even deeper than lexical activation. It has been suggested, in fact, that the N400 effect is a more sensitive measure of semantic activation than are behavioral measures (e.g., Heil et al., 2004; Rolke et al., 2001; Vogel et al., 1998). As a concrete example, Lien, Ruthruff, Cornett, Goodin, and Allen (2008) used N400 effects to determine whether people can extract word meaning while central attention is devoted to another task. Participants performed a tone-pitch Task 1 and a semantic relatedness Task 2 (whether the Task 2 word was related to a previously presented context word/category). The critical finding was the N400 effect declined sharply under dual-task conditions. They concluded that semantic activation of visual words is impaired while central attention is allocated to another task.

The Present Study

The present study used ERPs (i.e., the N400 effect) to assess whether semantic activation occurs for LEET stimuli just as strong as for regular words. Thus, regular words were included to provide a baseline for semantic activation. We adopted Lien et al.'s (2008) category judgment task, where participants memorized a category name prior to each block (e.g., fruit) and then determined whether a series of single stimuli (e.g., "APPLE" for the regular word or "4PPL3" for the LEET stimulus) were related or unrelated to that category. Stimulus type (words vs. LEET) varied within blocks.

Our main interest was the semantic activation of words and LEET stimuli as indicated by the N400 effect (the difference in ERPs between unrelated and related words). The semantic relatedness effect (the difference between unrelated and related words) on RT does not provide a clear picture regarding semantic activation for words and LEET stimuli since related and unrelated responses are made with different response fingers. Thus, the effect on RT could reflect a modulation of response decision processes (see the Discussion regarding problems interpreting semantic activation using behavioral data). Furthermore, since we compared the semantic activation between words and their corresponding LEET stimuli, word frequency and word length should have little influence on the comparison between them.

We expected to observe a large N400 effect for regular words, as previously shown in single-task conditions (e.g., Lien et al., 2008). The main question for the present study is whether similar N400 effects would also be observed for LEET stimuli formed by letters and digits. If LEET stimuli are processed like real words (i.e., if they can access word meaning), then LEET stimuli should produce similar N400 effects to regular words. Such a result not only would imply semantic activation for LEET stimuli but also would provide converging evidence for Perea et al. (2008)'s claim of full lexical activation for LEET stimuli.

Method

Participants. Twenty-four undergraduates (native English speakers) at Oregon State University participated in this experiment. Data from two of these participants were excluded due to excessive eye movement artifacts in the electroencephalographic (EEG) data (see below). The remaining 22 participants (16 females) had a mean age of 20 years (range: 18-27).

Apparatus, Stimuli, and Procedure. Stimuli were displayed on a 19-inch monitor and were viewed from a distance of about 55 cm. The category presented prior to each block was in lowercase, whereas the stimulus for each trial was a string of uppercase letters (words) or a mixture of letters and digits (LEET stimuli) printed in white, against a black background, in the center of the screen. LEET stimuli were formed by changing some letters in a word using digits similar in shape with their corresponding uppercase letters. That is, digit 1 was for letter L, digit 3 for letter E, digit 4 for letter A, digit 5 for letter S, digit 6 for letter G, and digit 0 for letter O. The digit substitution ranged from 30% to 64% (mean: 43%) across letter positions. Each letter and digit subtended a visual angle of approximately 1.15° in width × 1.25° in height.

Each trial started with a fixation cross in the screen center for 1,200 ms, which was then replaced by the stimulus until a response was made. Next, auditory feedback (a tone on error trials, silence on correct trials) was presented for 100 ms. The next trial then began with the fixation display. The participant's task was to indicate whether the stimulus was related or unrelated to the category for that block by pressing the leftmost response-box button for related and the rightmost button for unrelated. They were also told that some words were formed by digits and letters, which they should treat like regular words and determine the semantic relatedness to the current category. Speed and accuracy were emphasized equally.

A total of 20 categories were used for experimental blocks and 2 categories were used for practice blocks, taken from Lien et al. (2008) (see Appendix for the complete list).[1] Each participant performed two sessions. The first session contained one practice block of 36 trials, randomly selected from the two practice block categories, followed by 20 experimental blocks of 36 trials each (9 related words, 9 related LEETs, 9 unrelated words, and 9 unrelated LEETs, randomly determined). The second session contained the same 20 categories of experimental blocks as the first session except that the related/unrelated words and LEET stimuli were different. The order of the categories for experimental blocks was randomly determined for each participant. For each participant, each word and LEET stimulus appeared twice through the whole experiment – once for the related list and once for the unrelated list, in a random order. Participants completed these two sessions within a single visit to the lab and were given breaks between blocks and sessions.

EEG Recording and Analyses. The EEG activity was recorded from electrodes F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, and O2. These sites and the right mastoid were recorded in relation to a reference electrode at the left mastoid. The EEGs were then re-referenced offline to the average of the left and right mastoids. The horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and vertical electrooculogram (VEOG) was recorded from electrodes above and below the midpoint of the left eye. Electrode impedance was kept below 5 kΩ. EEG, HEOG, and VEOG were amplified using Synamps2 (Neuroscan) with a gain of 2,000, a bandpass of 0.1-70 Hz, and digitized at 250 Hz.

Trials with possible ocular and movement artifacts were identified using a threshold of ± 75µV for a 1,400 ms epoch beginning 200 ms before stimulus onset to 1,200 ms after stimulus onset. Each of these artifact trials were then inspected manually. This procedure led to the rejection of 7% of the trials, with no more than 25% rejected for any individual.

Results

In addition to trials with ocular artifacts, trials were excluded from the analyses of behavioral data (RT and proportion of error) and ERP data if RT was less than 100 ms or greater than 2,000 ms (0.4% of trials exceeded these cutoff values). Incorrect response trials were also excluded from RT and ERP analyses. Analysis of variance (ANOVA) was used for all statistical analyses. Whenever appropriate, p values were adjusted using the Greenhouse-Geisser epsilon correction for nonsphericity.

Behavioral Data Analyses. The ANOVAs on RT and proportion of error were conducted as a function of stimulus type (word vs. LEET) and semantic relatedness (related vs. unrelated). Table 1 shows mean RT and proportion of error for each condition. Analyses revealed that overall RT was 41 ms longer for LEET stimuli than word stimuli, $F(1, 21) = 103.76$, $p < .0001$, $\eta_p^2 = .83$. Mean RT was 44 ms longer for unrelated stimuli (677 ms) than related stimuli (633 ms), $F(1, 21) = 44.62$, $p < .0001$, $\eta_p^2 = .68$. The semantic relatedness effect (Unrelated – Related) on RT was larger for LEET stimuli than words (58 ms vs. 29 ms, respectively), $F(1, 21) = 22.91$, $p < .0001$, $\eta_p^2 = .52$. Further *t*-test analyses revealed that the semantic relatedness effect was significant both for LEET stimuli, $t(21) = 7.31$, $p < .0001$, and words, $t(21) = 4.58$, $p < .001$.

For the proportion of error data, LEET stimuli produced higher error rates than word stimuli (.085 vs. .072), $F(1, 21) = 27.73$, $p < .0001$, $\eta_p^2 = .57$. The error rate was also higher for related stimuli (.100) than unrelated stimuli (.056), $F(1, 21) = 28.83$, $p < .0001$, $\eta_p^2 = .58$. However, the semantic relatedness effect on error rate was similar for LEET stimuli and words (-.047 vs. -.041, respectively), $F < 1.0$. As in RT, further *t*-test analyses revealed that the semantic relatedness effect was significant both for LEET stimuli, $t(21) = 5.08$, $p < .0001$, and words, $t(21) = 4.97$, $p < .0001$.

ERP Analyses. The averaged ERP waveforms were time-locked to stimulus onset. For each stimulus type (word vs. LEET), difference waves were constructed by subtracting the ERP waveforms elicited by stimuli related to the category from the ERP waveforms elicited by stimuli unrelated to the category (i.e., the N400 effect). We collapsed across the three frontal electrode sites (F3, Fz, & F4), the three central electrode sites (C3, Cz, & C4), and the three parietal electrode sites (P3, Pz, & P4). Following Lien et al. (2008; see also Vogel et al., 1998), the mean amplitude of the N400 effect was measured from 400-600 ms after stimulus onset relative to the 200-ms baseline period before stimulus onset. This is the time window during which the N400 effect is typically maximal (see Figure 1). An ANOVA on the N400 amplitudes (difference waveforms = unrelated ERPs – related ERPs) was conducted as a function of stimulus type (word vs. LEET) and electrode sites (frontal [F3,Fz,F4], central [C3,Cz,C4], parietal [P3,Pz,P4]). Figure 2 shows the grand average waveform for related and unrelated stimuli for these electrodes and Figure 3 shows the mean N400 amplitudes.

The N400 effect was similar for both words and LEET stimuli (-3.568 μV vs. -3.848 μV, respectively), $F(1, 21) = 1.51$, $p = .2329$, $\eta_p^2 = .03$. Further *t*-test analyses revealed that the N400 effect was significantly greater than zero both for words, $t(21) = -12.88$, $p < .0001$, and LEET stimuli, $t(21) = -13.35$, $p < .0001$. Although the overall N400 effect was much larger for the central (-4.050 μV) than the frontal and parietal sites (-3.585 μV vs. -3.488 μV), $F(2, 42) = 7.23$, $p < .01$, $\eta_p^2 = .26$, the difference in the N400 effect between words and LEET stimuli did not interact with electrode site, $F < 1.0$.

Discussion

The present study used the N400 effect to examine whether semantic activation occurs for LEET stimuli (formed by letters and digits) just as strong as for regular words. In each trial, participants made a category judgment on either the LEET stimuli or regular words (formed by uppercase letters), intermixed within blocks. An advantage of using a single stimulus presentation in our study is that it eliminated unwanted effects of extraneous stimuli, such as the possible forward masking interference produced by the priming paradigm (e.g., Forster, 1998). The critical finding is that the N400 effect at all three electrode sites (frontal, central, and parietal) was similar in magnitude for both LEET and regular words, suggesting that semantic activation occurs for LEET stimuli just as strong as for regular words. Since it has been suggested that semantic activation is a result of lexical activation (e.g., Besner et al., 1999), we conclude that, in the presence of a top-down context (e.g., semantic categories), letter-like digits embedded in a word are able to activate both lexical and semantic information.

Another interesting finding of the present study is the apparent trend towards earlier N400 onset for word than LEET stimuli (about 40 ms; see Figure 3). Thus, even though the digits in LEET stimuli can be encoded in a letter-like manner and subsequently activate semantic information, the regular words have faster access to the mental lexicon due to greater familiarity. The behavioral data (e.g., RT) are also consistent with this claim, showing that faster semantic-relatedness judgments occurs for words than LEET stimuli. This finding seems to suggest that processing stages prior to semantic activation might have delayed for LEET stimuli (e.g., encoding) but that semantic analysis of the encoded letter representations is not affected at all.

We noted earlier that the use of behavioral data (e.g., RT) opens the door to numerous alternative explanations for the priming effect with LEET stimuli, such as prelexical processing or less disruptive visual similarity between prime and target, rather than the lexical activation interpretation favored by Perea at al. (2008). Likewise, our behavioral data may not provide clear evidence for semantic activation in LEET stimuli. We found a positive semantic relatedness effect on RT (slower for unrelated than related stimuli) but a negative effect on errors (smaller error rates for unrelated than related stimuli), indicating a speed-accuracy tradeoff. This finding underscores another major limitation of behavioral measures – they are sensitive to response bias (e.g., Green & Swets, 1966). On the positive side, however, it also highlights one major advantage of N400 measures, as used in the present study; that is, they more specifically reflect the buildup of semantic activation with little constraint from decision-making (e.g., Heil et al., 2004; Rolke et al, 2001; for a review, Kutas & Federmeier, 2011).

Our N400 data provided clear evidence for semantic activation in LEET stimuli. Alternatively, the activation could be due to top-down expectancy, as participants already knew what category to look for in each block. Although we always presented a single stimulus (either a LEET stimulus or a regular uppercase word in each trial), those stimuli were assessed in terms of their fit within a semantic category presented prior to each block. In this light, the finding that LEET stimuli elicited the N400 effect similar in magnitude to that for regular words suggests that the N400 effect is not an indicator of perceptual integration of lexicality (as the mixture of digits within letters in LEET stimuli would have rendered the encoding of lexical representation, and with little semantic information being activated). Rather, it more likely reflects a post-lexical process that is driven by context integration such as categories (e.g., Brown & Hagoort, 1993; Kutas & Federmeier, 2011; but see Deacon, Hewitt, Yang, & Nagata, 2000, for a case where the N400 effect occurred without conscious awareness of word identity).

One constraint of our study is that the effects of letter vs. digit position in LEET stimuli and the number of digit replacements in LEET stimuli may have played a role in semantic activation.[2] For instance, as observed by Jordan, Thomas, Patching, and Scott-Brown (2003), when words were presented in passages of text, visually degrading the exterior letters of a word (the first and last positions, such as "d_ _k" for the word "dark") slowed the reading rate more than visually degrading interior letters (all letter positions that lie between the first and last positions, such as "_ar_" for the word "dark"). They therefore argued that exterior letters of words play a major role in visual word recognition (see also Jordan, Thomas, & Scott-Brown, 1999, with a single word presentation rather than passages). In the present study, about 55% of LEET stimuli replaced at least one of the exterior letters with a digit (30% and 34%, respectively, of the first and last letters were replaced, and both positions were replaced for 9% of stimuli). If semantic access was restricted to digit replacements only in interior locations or only in exterior locations, then one would expect the N400 effect elicited by the LEET stimuli to be smaller than the effect elicited by the regular words. In contrast to this prediction, our results showed that the N400 effect for LEET stimuli was about 8% larger in magnitude than the effect for regular words. Thus, the present N400 effect for LEET stimuli was not due solely to an "exterior letter effect". The present LEET results, along with Jordan and colleagues' earlier letter-position work and the case mixing results of Allen et al. (2009) and Lien, Allen, and Crawford (2012), suggest that "coarse-scale" information in words (i.e., the cursory shape of the whole word; Jordan et al., 2003) is involved in visual word recognition in addition to individual letter identities. This appears to be the case because all of these studies suggest that the physical identity of individual letters is not the only information used to encode words.

In sum, we have demonstrated that LEET stimuli gain lexical access and activate semantic information using electrophysiological measures (i.e., N400 effects). It is clear that the exact identity of components in a word, such as digits instead of letters, does not hinder semantic activation even though the encoding is slower than for regular words. Thus, we extended Perea et al.'s (2008) priming results to a category task and showed that the processing equivalence applies even to deeper levels of word processing (i.e., access to word meaning).

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Appendix

Category labels (in bold) and their members in words and LEET stimuli used in the experiment. The unrelated words were selected from different categories, with the restriction that each word and LEET stimulus appeared exactly once in the related condition and once in the unrelated condition. The last two categories (emotion/expression/feeling and sports) were used for practice blocks. However, each participant received only one of them, randomly determined.

mammals		**body parts**		**transportations**	
Word	LEET	Word	LEET	Word	LEET
GORILLA	G0R1LL4	EAR	34R	TRAWLER	TR4WL3R
PIG	P16	TONGUE	T0N6U3	CART	C4RT
DEER	D33R	SHIN	5H1N	KAYAK	K4Y4K
ZEBRA	Z3BR4	HEEL	H33L	PLANE	PL4N3
RABBITT	R4881TT	FOOT	F00T	YACHT	Y4CHT
GIRAFFE	6IR4FF3	LEG	L3G	CAR	C4R
SHEEP	SH33P	EYE	3Y3	TRAILER	TR41L3R
WOLF	W0LF	NECK	N3CK	SHIP	SH1P
TIGER	T163R	HEAD	H34D	WAGON	W460N
APE	4P3	ELBOW	3LB0W	TRAM	TR4M
BEAVER	B34V3R	WRIST	WR15T	SLED	5L3D
COYOTE	C0Y0T3	CHEEK	CH33K	CANOE	C4N03
BEAR	834R	KNEE	KN33	VAN	V4N
CHICKEN	CH1CK3N	TOE	T03	TRAIN	TR41N
GOAT	GO4T	ANKLE	4NKL3	BIKE	B1K3
CAT	C4T	ARM	4RM	BOAT	B04T
MOOSE	M00S3	JAW	J4W	BUS	8U5
COW	C0W	FINGER	F1N63R	TROLLEY	TR0LL3Y

birds		**bugs**		**clothing**	
Word	LEET	Word	LEET	Word	LEET
HAWK	H4WK	GNAT	6N4T	SHORTS	5H0RT5
PIGEON	P1630N	SLUG	5LU6	CAP	C4P
FALCON	F4LC0N	BEE	B33	SHOE	5H03
HERON	H3R0N	WASP	W45P	BOOT	800T
SPARROW	5P4RR0W	LICE	L1C3	ROBE	R083
ROBIN	R0B1N	ANT	4NT	HAT	H4T
RAVEN	R4V3N	CRICKET	CR1CK3T	GLOVE	6L0V3
SEAGULL	S34GULL	TERMITE	T3RM1T3	JACKET	J4CK3T
CRANE	CR4N3	BEETLE	833T13	SKIRT	5K1RT
SWAN	5W4N	HORNET	H0RN3T	JEANS	J34N5
PERROT	P3RR0T	CICADA	C1C4D4	SOCK	50CK

PARROT	P4RR0T	APHID	4PH1D	SWEATER	5W34T3R
CHICKEN	CH1CK3N	FLEA	FL34	HOSE	H053
PELICAN	P3L1C4N	SPIDER	5P1D3R	SHIRT	5H1RT
PEACOCK	P34C0CK	FIREFLY	F1R3FLY	DRESS	DR355
GOOSE	G00S3	ROACH	R04CH	COAT	C04T
EAGLE	346L3	LADYBUG	L4DYBU6	PANTS	P4NT5
DOVE	D0V3	MAGGOT	M4660T	SCARF	5C4RF

family member		**musical instrument**		**fruit**	
Word	LEET	Word	LEET	Word	LEET
COUSIN	C0U51N	BAGPIPE	B46P1P3	GUAVA	GU4V4
GRANDMA	6R4NDM4	GUITAR	6U1T4R	LIME	L1M3
NIECE	N13C3	HARP	H4RP	PEAR	P34R
NEPHEW	N3PH3W	OBOE	0B03	BANANA	B4N4N4
WIFE	W1F3	CYMBALS	CYMB4L5	ORANGE	0R4N63
MOTHER	M0TH3R	CELLO	C3LL0	APPLE	4PPL3
UNCLE	UNC13	VIOLIN	V10L1N	APRICOT	4PR1C0T
DAD	D4D	BASS	B455	BERRY	83RRY
SISTER	515T3R	VIOLA	V1OL4	NECTARINE	N3CT4RIN3
SIBLING	51BL1N6	ORGAN	0R64N	MANGO	M4NG0
SPOUSE	5P0U53	PICCOLO	P1CC0L0	GRAPE	GR4P3
PARENT	P4R3NT	BASSOON	845500N	FIG	FI6
AUNT	4UNT	TUBA	TU84	RAISIN	R41S1N
FATHER	F4TH3R	BANJO	B4NJ0	AVACADO	4V4C4D0
SON	S0N	CLARINET	CL4R1N3T	LEMON	L3M0N
GRANDPA	6R4NDP4	PIANO	P14N0	MELON	M3L0N
BROTHER	BR0TH3R	FIDDLE	F1DDL3	PEACH	P34CH
HUSBAND	HU5B4ND	BUGLE	BU6L3	PAPAYA	P4P4Y4

vegetables		**trees/flowers/plants**		**furniture**	
Word	LEET	Word	LEET	Word	LEET
CELERY	C3L3RY	GRASS	6R455	DRAWER	DR4W3R
BEANS	B34N5	CEDAR	C3D4R	DRESSER	DR3553R
POTATO	P0T4T0	ROSE	R053	CHAIR	CH41R
LETTUCE	L3TTUC3	ELM	3LM	TABLE	T4BL3
ONION	0N10N	ASH	45H	CABINET	C4B1N3T
PEPPER	P3PP3R	BEECH	B33CH	ARMOIRE	4RM01R
CARROT	C4RR0T	MAPLE	M4PL3	BED	B3D
SPINACH	5P1N4CH	BUCKEYE	BUCK3Y3	ROCKER	R0CK3R
BEETS	B33T5	GINKO	61NK0	STOOL	5T00L
RADISH	R4D15H	SPRUCE	5PRUC3	DESK	D35K
LEEK	L33K	REDWOOD	R3DW00D	RACK	R4CK
CABBAGE	C4BB463	FERN	F3RN	SHELF	5H3LF
PEA	P34	OAK	04K	VANITY	V4N1TY
GARLIC	64RL1C	LILAC	L1L4C	STAND	5T4ND
SPROUTS	5PR0UT5	CYPRESS	CYPR355	CHEST	CH35T

YAM	Y4M	VIOLET	V10L3T	BENCH	83NCH
PEANUT	P34NUT	PEONY	P30NY	SOFA	50F4
SQUASH	5QU45H	PINE	P1N3	LAMP	L4MP

occupations

Word	LEET
ACTOR	4CT0R
JANITOR	J4N1T0R
BANKER	B4NK3R
LAWYER	L4WY3R
CLERK	CL3RK
ARTIST	4RT15T
FARMER	F4RM3R
JUDGE	JUD63
BARBER	B4RB3R
TEACHER	T34CH3R
MANAGER	M4N463R
CHEF	CH3F
BAKER	B4K3R
SAILOR	S41L0R
WRITER	WR1T3R
THERAPIST	TH3R4PI5T
COACH	C04CH
FIREMAN	F1R3M4N

money

Word	LEET
EURO	3UR0
BILL	81LL
DOLLAR	D0LL4R
BUCK	8UCK
LOAN	L04N
CASH	C45H
DIME	D1M3
COIN	C01N
DEBT	D38T
QUARTER	QU4RT3R
YEN	Y3N
CREDIT	CR3D1T
NICKEL	N1CK3L
ACCOUNT	4CC0UNT
PAY	P4Y
CHECK	CH3CK
PENNY	P3NNY
PESO	P3S0

room/place in a house

Word	LEET
PATIO	P4T10
DOORWAY	D00RW4Y
PARLOR	P4RL0R
GARAGE	G4R46E
CELLAR	C3LL4R
KITCHEN	K1TCH3N
ATRIUM	4TR1UM
BALCONY	84LC0NY
HALLWAY	H4LLW4Y
PANTRY	P4NTRY
FOYER	F0Y3R
ATTIC	4TT1C
DEN	D3N
BEDROOM	B3DR00M
STEPS	5T3P5
DECK	D3CK
CLOSET	CL0S3T
STAIRS	ST4IR5

cooking tools/appliances

Word	LEET
PEELER	P33L3R
FRIDGE	FR1D63
SPATULA	5P4TUL4
GRILL	6R1LL
TOASTER	T045T3R
KNIFE	KN1F3
FAUCET	F4UC3T
BASTER	B45T3R
SINK	51NK
WHISK	WH15K
OVEN	0V3N
BLENDER	8L3ND3R
MIXER	M1X3R
GRATER	6R4T3R
PAN	P4N
STOVE	5T0V3
TEAPOT	T34P0T
LADLE	L4DL3

geographical features

Word	LEET
OCEAN	0C34N
STREAM	5TR34M
FOREST	F0R35T
DESERT	D353RT
BEACH	B34CH
SEA	S34
CANYON	C4NY0N
BROOK	8R00K
CAVE	C4V3
MEADOW	M34D0W
CANAL	C4N4L
LAKE	L4K3
VALLEY	V4LL3Y
SWAMP	5W4MP
CREEK	CR33K
ISLAND	15L4ND
BAY	84Y
RIVER	R1V3R

weather

Word	LEET
SLEET	5L33T
DRIZZLE	DR1ZZL3
RAINBOW	R41N80W
TWISTER	TW15T3R
HAIL	H41L
MIST	M15T
CYCLONE	CYC10N3
GALE	64L3
BREEZE	BR33Z3
FROST	FR05T
RAIN	R41N
TORNADO	T0RN4D0
SKY	5KY
STORM	5TR0RM
FOGGY	F066Y
SNOW	5N0W
HAZY	H4ZY
SHOWER	5H0W3R

colors		**fish**		**emotion/expression/feeling**	
Word	LEET	Word	LEET	Word	LEET
BLACK	8L4CK	EEL	33L	FEAR	F34R
WHITE	WH1T3	SOLE	50L3	TERROR	T3RR0R
TAN	T4N	PERCH	P3RCH	FURIOUS	FUR10U5
SILVER	51LV3R	BASS	B455	UPSET	UP53T
YELLOW	Y3LL0W	HALIBUT	H4L18UT	SAD	54D
CYAN	CY4N	GROUPER	6R0UP3R	DESIRE	D351R3
GRAY	6R4Y	SALMON	54LM0N	ANGER	4N63R
INDIGO	1ND160	SHARK	5H4RK	DISGUST	D156U5T
MAGENTA	M463NT4	CARP	C4RP	BLISS	BL155
VIOLET	V10L3T	HADDOCK	H4DD0CK	LUST	LU5T
BRONZE	8R0NZ3	TUNA	TUN4	HOPE	H0P3
BLUE	8LU3	SARDINE	54RD1N3	ANXIETY	4NX13TY
GREEN	6R33N	MARLIN	M4RL1N	GREED	6R33D
RED	R3D	WALLEYE	W4LL3Y3	HAPPY	H4PPY
MAROON	M4R00N	SQUID	5QU1D	MAD	M4D
BROWN	8R0WN	HERRING	H3RR1N6	GRUMPY	6RUMPY
GOLD	60LD	CATFISH	C4TF15H	ENVY	3NVY
BEIGE	B31G3	SNAPPER	5N4PP3R	GLAD	6L4D

sports	
Word	LEET
TRACK	TR4CT
BOXING	B0X1N6
SURFING	5URF1N6
FENCING	F3NC1N6
TENNIS	T3NN15
CYCLING	CYCL1N6
GOLF	60LF
RUGBY	RU68Y
RACING	R4C1N6
SKIING	5K11N6
HOCKEY	H0CK3Y
ROWING	R0W1N6
CROQUET	CR0QU3T
SOCCER	50CC3R
ARCHERY	4RCH3RY
KARATE	K4R4T3
BOWLING	80WL1N6
DIVING	D1V1N6

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Footnotes

1. In order to form LEET stimuli, it is necessary to replace some words from Lien et al.'s (2008) list. It should be noted that it is very difficult to generate items for each category that can be substituted by digits. Therefore, instead of requiring LEET stimuli to have at least three digits as Perea et al.'s (2008) study, we required at least one digit.
2. We did not design our study to examine the effect of the number or position of digit replacements in LEET stimuli. Across all LEET stimuli, 14%, 50%, 30%, and 6% contained one, two, three, and four digits, respectively (additionally, one LEET stimulus had 5 digits and one had 6 digits). The percentage of digit replacement in Positions 1 to 9 of the LEET stimuli ranged from 30% to 64%. Since the design was unbalanced, analyzing N400 effects and behavioral data as a function of these two variables would be biased. Most importantly, breaking down N400 effects as a function of these two variables will result in small samples, leaving noising data.

Table 1.

Mean Response Time (in Milliseconds) and Proportion of Error as a Function of Semantic Relatedness (Related vs. Unrelated) for Word and LEET.

	Semantic Relatedness	
	Related	Unrelated
	Response Time	
Word	620 (14)	649 (17)
LEET	647 (15)	705 (20)
	Proportion of Error	
Word	.095 (.014)	.049 (.006)
LEET	.106 (.012)	.064 (.009)

Note: The standard error of the mean is shown in parentheses.

Figure Captions

Figure 1. The scalp topography of the N400 effect (difference = Unrelated ERPs – Related ERPs) for word and LEET stimuli during the time window 400-600 ms after stimulus onset. ERP: Event-related potential.

Figure 2. Grand average event-related brain potentials as a function of semantically related and unrelated word and LEET at the frontal electrode sites (data collapsed across the F3, Fz, and F4), central electrode sites (data collapsed across the C3, Cz, and C4), and parietal electrode sites (data collapsed across the P3, Pz, and P4). Negative is plotted upward and time zero represents stimulus onset. The baseline period was the 200 ms prior to stimulus onset.

Figure 3. Grand average difference in event-related brain potentials, formed by subtracting semantically related trials from semantically unrelated trials (i.e., the N400 effect), for word and LEET at the frontal electrode sites (data collapsed across the F3, Fz, and F4), central electrode sites (data collapsed across the C3, Cz, and C4), and parietal electrode sites (data collapsed across the P3, Pz, and P4). The unfilled rectangular boxes indicate the time window used to assess the N400 effect (400-600 ms after stimulus onset). Negative is plotted upward and time zero represents stimulus onset. The baseline period was the 200 ms prior to stimulus onset.

Figure 1

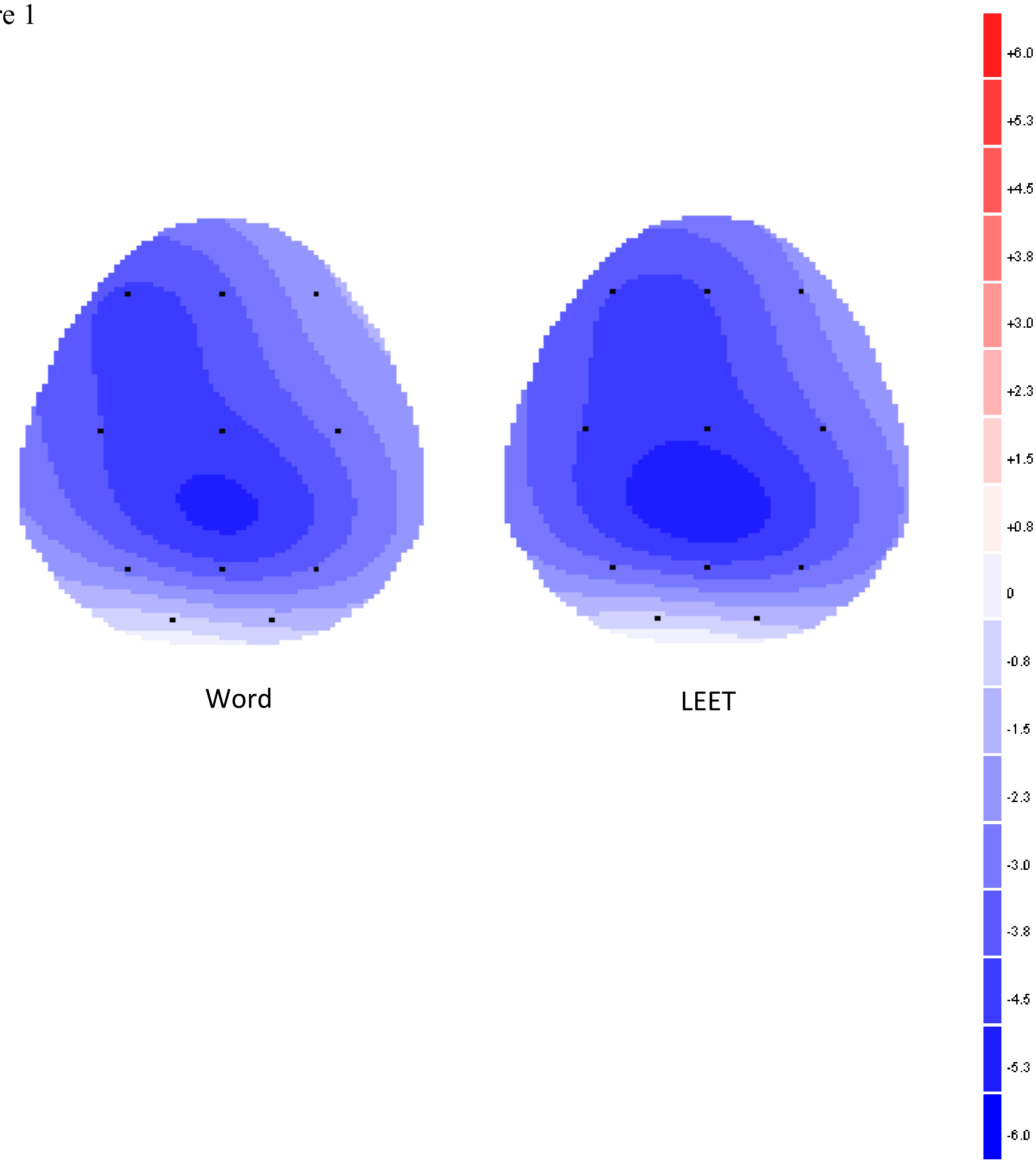


Figure 2

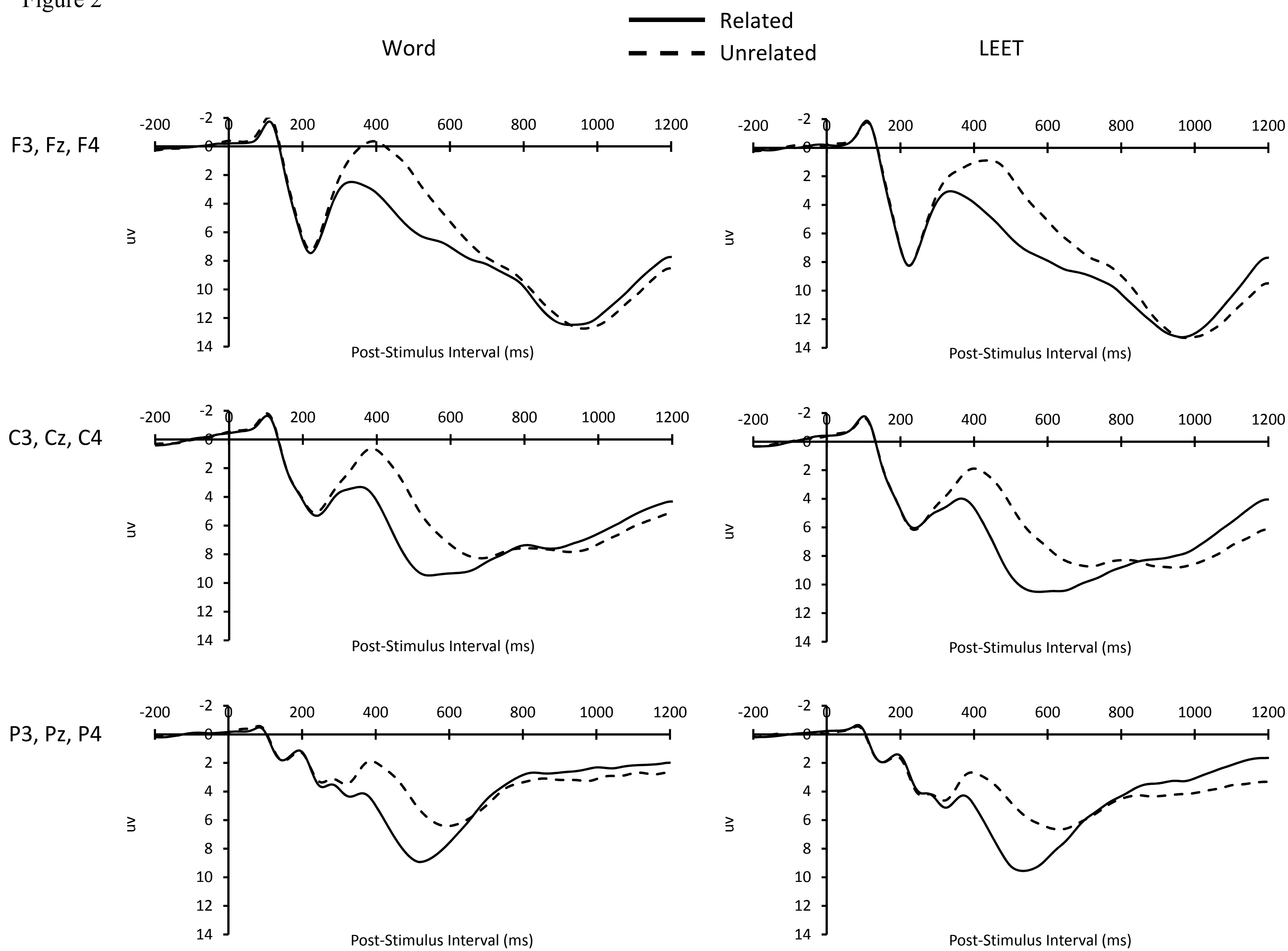
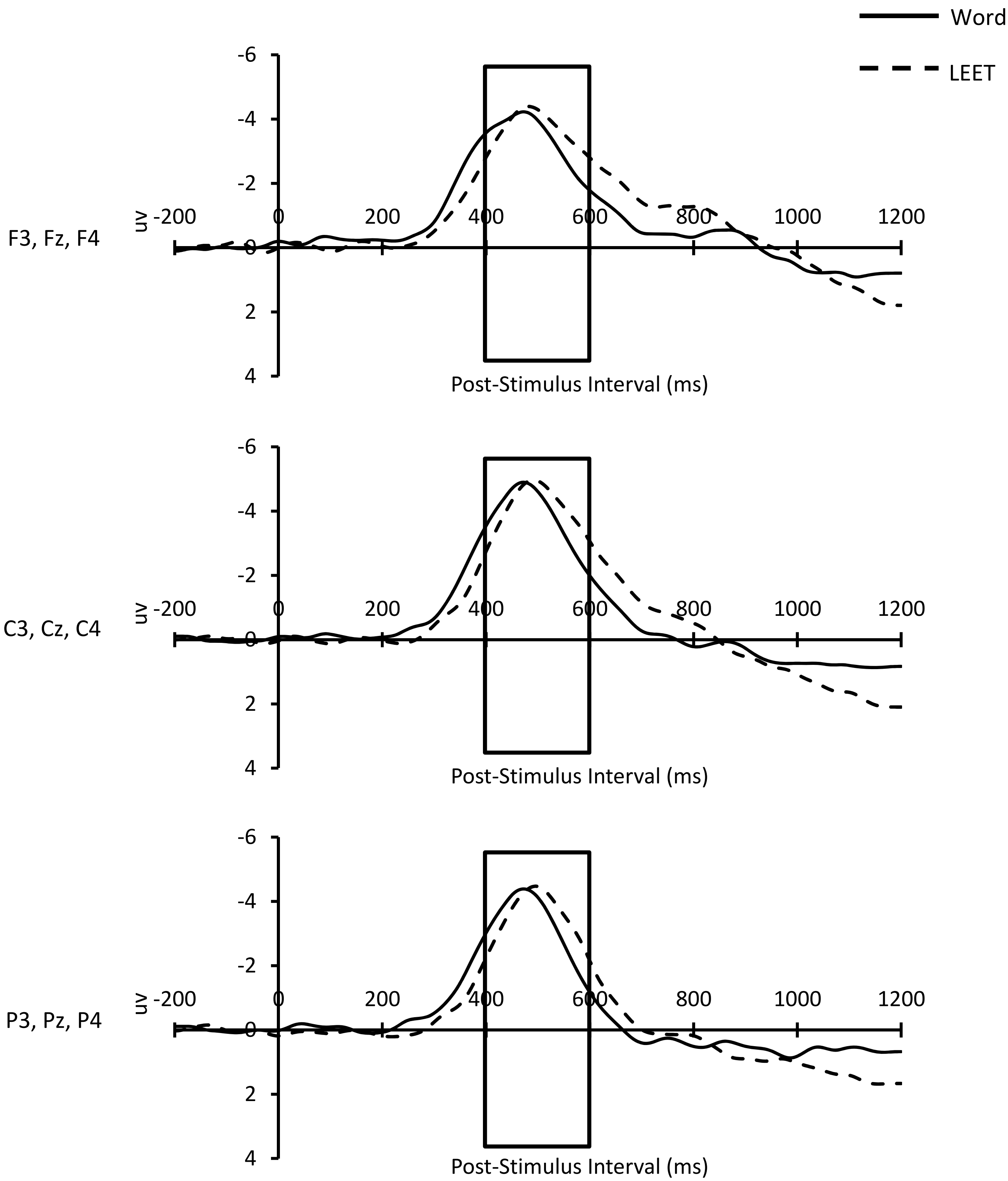

Related
Unrelated
Word
LEET
F3, Fz, F4
C3, Cz, C4
P3, Pz, P4
-200
0
200
400
600
800
1000
1200
-2
0
2
4
6
8
10
12
14
uv
Post-Stimulus Interval (ms)

Figure 3


Word
LEET
F3, Fz, F4
C3, Cz, C4
P3, Pz, P4
uv
-6
-4
-2
0
2
4
-200
0
200
400
600
800
1000
1200
Post-Stimulus Interval (ms)