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Minding the PS, queues, and PXQs: Uniformity of semantic processing across multiple stimulus types

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Abstract

An assumption in the reading literature is that access to semantics is gated by stimulus properties such as orthographic regularity or familiarity. In the electrophysiological domain, this assumption has led to a debate about the features necessary to initiate semantic processing as indexed by theN400 event-related potential (ERP) component. To examine this, we recorded ERPs to sentences with endings that were familiar and legal (words), familiar and illegal (acronyms), or unfamiliar and illegal (consonant or vowel strings). N400 congruency effects (reduced negativity to expected relative to unexpected endings) were observed for words and acronyms; these were identical in size, timing, and scalp distribution. Notably, clear N400 potentials were also elicited by unfamiliar, illegal strings, suggesting that, at least in a verbal context, semantic access may be attempted for any letter string, regardless of familiarity or regularity.

Descriptors

Event-related potentials (ERPs); N400; Semantic access; Visual word recognition

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The ubiquity of instant messaging, text messaging, and complicated technologies abbreviated with brief sequences of letters (e.g., HDTV, DVR, GPS) is increasingly bombarding literate adults with meaningful strings that defy English spelling convention. That developed readers seem able to easily assign meanings to letter strings for which a pronunciation cannot be readily computed by common spelling-to-sound production rules is more than an interesting fact, as it bears directly on debates in the reading literature about the nature of the computations involved in linking an orthographic word form with semantics. On the one hand, a long-standing view stemming from neuropsychological research (dating back to, for example, Dejerine, 1891) and supported by recent neuroimaging data (e.g., Pugh et al., 2000) states that written words can take one of two functionally and anatomically distinct routes to semantics. On the other hand, some behavioral (e.g., McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) and computational (e.g., Harm & Seidenberg, 2004) work has suggested instead that the cognitive processes mediating between orthographic input and semantic access are functionally uniform and utilize broadly distributed representations.

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The neuropsychological tradition stresses the importance of orthographic regularity in determining whether a written string will take a phonologically mediated or direct route to semantics. Strings for which a correct pronunciation can be computed on the basis of common spelling-to-sound rules (e.g., SIGMA) are first translated from the written, orthographic representation to a phonological representation, from which semantics can be retrieved. Very high frequency strings, or strings with irregular spelling-to-sound correspondences (e.g., YACHT), are instead linked to their associated semantics via an orthographic, not phonological, lexicon. The translated route is thought to rely on temporoparietal brain areas including the angular gyrus, supra-marginal gyrus, and posterior superior temporal gyrus, whereas the associative route is thought to rely on more ventral areas such as the middle temporal and middle occipital gyri (Pugh et al., 2000). In computational models instantiating two reading routes (“dual process models”; e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), orthographic regularity is a formally represented property, because the rules used in the translated route are binary and only include the most common spelling-to-sound correspondences in written English. Words with irregular spelling-to-sound relationships, therefore, cannot take the phonologically mediated path and still be translated correctly.

In contrast, functionally homogenous models from the connectionist tradition tend to stress the importance of statistical consistencies in language, typically suggesting that rulelike behavior can emerge from a system with no formally instantiated rules. Models such as that of Harm and Seidenberg (2004) are able to produce correct pronunciations for novel, regular pseudowords because they are able to learn, for example, that the pronunciation of word final AT will typically be/æt/and the pronunciation of word initial K will typically be/k/, enabling them to produce the normatively correct pronunciation/kæt/for the pseudoword KAT, even without instantiating spelling-to-sound rules or having ever been trained on that specific item. Connectionist models are often trained in a frequency-biased manner; items in the training corpus with high frequency are presented to the model more often during training than items with low frequency. Because of this frequency bias and the notable ability of computational models to learn statistical consistencies, connectionist models, although not formally representing orthographic regularity, are intrinsically sensitive to what in a human would be called stimulus familiarity, including familiarity for subparts of words.

Although a large body of behavioral, neuropsychological, and hemodynamic imaging work has been brought to bear on the debate over the relative import of orthographic regularity and frequency for word recognition, neither theoretical tradition has substantially taken advantage of electrophysiological data—a gap in the literature that is regrettable given the suitability of the fast, functionally decomposable bioelectromagnetic signal to the study of online language processing. Electrophysiological investigations of the time course of visual word recognition suggest a temporally extended process of categorizing inputs as wordlike. The process seems to begin around 95 ms, with a negativity over midline occipital sites that distinguishes the response to objectlike stimuli from those to orthographic strings, followed approximately 30 ms later by a further distinction between strings composed of real letters and nonletters (Schendan, Ganis, & Kutas, 1998; for related MEG studies, see also Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003; Tarkiainen, Cornelissen, & Salmelin, 2002). Intracranial recording and fMRI studies suggest that such differentiations may be occurring in the posterior fusiform gyrus (Nobre, Allison, &McCarthy, 2002) and the occipitotemporal and inferior occipital sulci (Puce, Allison, Asgari, Gore, & McCarthy, 1996). Random letter strings are differentiated from pronounceable letter strings and words beginning approximately 400 ms after stimulus onset in the ERP (Nobre et al., 2002).

Beginning around the time that the system begins to appreciate the difference between random strings and more structured or more familiar ones, there are also the first indications that visual inputs are being treated as lexical or semantic in nature. For example, differences in magnetic activity between auditorally and visually presented words have been shown to disappear by approximately 400 ms after stimulus onset, at which time activation initially determined by presentation modality converges in the anterior temporal and left inferior prefrontal cortices (Marinkovic et al., 2003), where form-general word processing is likely taking place. The electrophysiological response to words (in all modalities) in that same time period is characterized by a negative-going potential with a centro-posterior distribution, known as the N400 (Kutas & Hillyard, 1980); N400-like potentials have also been reported to pictures (Ganis, Kutas, & Sereno, 1996), faces (Bobes, Valdés-Sosa, &Olivares, 1994),meaningful environmental sounds (Van Petten & Rheinfelder, 1995), and gestures (Kelly, Kravitz, & Hopkins, 2004). N400 amplitude is modulated by factors known to affect ease of semantic access, including repetition, word frequency, and the presence of supportive contextual information (for a review, see Kutas & Federmeier, 2000), but not by most syntactic (Kutas & Hillyard, 1983) or perceptual (Kutas & Hillyard, 1980) manipulations. Thus, the N400 seems to be a functionally specific marker of lexico-semantic processing.

Although the N400 has sometimes been interpreted as reflecting postlexical integration of semantics into a sentential context (e.g., Stuss, Picton,& Cerri, 1988), there is evidence from a number of lines of work suggesting that the N400 also (or instead) reflects more automatic aspects of lexical or even prelexical processing. For example, N400 effects can be observed under masked stimulus presentation conditions (Brown & Hagoort, 1993; Deacon, Hewitt, Yang, & Nagata, 2000), during the attentional blink (Misra & Holcomb, 2003), during implicit recognition in amnesia (Olichney et al., 2000), and even during some stages of sleep (Bastuji, Perrin, & Garcia-Larrea, 2002). Indeed, the N400 is quite sensitive to a number of lexical characteristics, even when ERPs are collected in response to heterogenous items presented in a list, where no discourse level integration is likely to be occurring (Deacon, Dynowska, Ritter, & Grose-Fifer, 2004; Holcomb, Grainger, & O'Rourke, 2002; Laszlo & Federmeier, 2007b; Rugg & Nagy, 1987).

Studies presenting stimuli in a list format have reported that words and orthographically regular pseudowords elicit clear N400 potentials, whereas illegal strings of letters do not (Holcomb & Neville, 1990; Rugg & Nagy, 1987). This type of finding raises a question analogous to that in the reading literature about the nature of the low-level stimulus properties the system might use to determine whether semantic access is attempted. Deacon and colleagues (2004) have suggested that orthographic regularity might be the critical gating factor. They examined the effects of repetition on pronounceable pseudowords that were either clearly derived from real words (e.g., BEEFLE, derived from BEETLE) or not clearly similar to any real word (e.g., SAKFEN.) Both derived and nonderived pseudowords elicited similar N400 repetition effects, which the authors interpreted as evidence that N400 processing can be engaged even by highly unfamiliar items, provided that those items are orthographically regular.

In contrast, work from our laboratory has suggested that stimulus familiarity may be more important than orthographic regularity in cuing the language processing system that N400 processing should be initiated. Specifically, we have demonstrated that when illegal but highly familiar acronyms (e.g., WWW, VCR) are repeated in a word list context, they elicit N400 repetition effects identical in magnitude, timing, and distribution across the scalp to those elicited by words or pseudowords (Laszlo & Federmeier, 2007b). This finding argues against the hypothesis that strings must be orthographically regular in order to elicit the processes indexed by the N400. We have additionally demonstrated that familiar acronyms show a performance benefit in the Reicher–Wheeler task, similar to that seen for words or pseudowords (Laszlo & Federmeier, 2007a): Letters in orthographically illegal acronyms are identified with significantly more accuracy than letters in unfamiliar illegal strings, even when presented in a two-alternative forced choice in which the incorrect choice also produces a familiar acronym (e.g., querying F or H in the second position for the target NHL). This finding strengthens the claim that the repetition effects we observed in our ERP study arose because of facilitated lexico-semantic access.

Our findings indicating that illegal acronyms, like words and pseudowords, can make rapid contact with high level lexico-semantic information argue against dual-process models of visual word recognition, which must predict that familiar but illegal acronyms be processed differently from unfamiliar but regular pseudowords. However, neither the word list task nor the Reicher–Wheeler task that we employed in our previous work required the processing of meaning for accurate performance; a stronger case for the role of stimulus familiarity in semantic access could be made by employing a reading task that required access to the meaning of the acronyms.

Furthermore, although the repetition effects we observed for illegal acronyms were identical to those for orthographically regular stimuli and different from those to unfamiliar illegal strings (which did not manifest ERP repetition effects; Laszlo & Federmeier, 2007b), the first presentation waveforms for acronyms were actually indistinguishable from those to the unfamiliar strings. Both elicited more positive responses in the N400 time window than did words or pseudowords, probably because these illegal stimulus classes were considerably lower in lexical density (i.e., Coltheart's *N*: the number of words that can be created from a word by single letter substitution), a factor known to affect N400 amplitude (Holcomb et al., 2002). The broad positivity elicited by illegal strings in list contexts has led to the inference that no N400-related activity is obtained for these items (e.g., Deacon et al., 2004; Rugg & Nagy, 1987). However, the fact that N400 repetition effects can be elicited for at least some items that do not manifest a clear N400 component on first presentation suggests that N400 activity can in some cases be masked by the more general waveform morphology, and thus raises the question of whether it is appropriate to conclude that even unfamiliar, illegal strings are not associated with attempts at lexico-semantic access.

To address the related issues of possible filters on N400 processing and whether or not illegal strings of letters can elicit attempts at lexico-semantic access, specifically as indexed by the N400, in the present study we examined and compared the processing of words, familiar (but orthographically illegal) acronyms, and unfamiliar illegal strings using the classic N400 sentence anomaly paradigm (Kutas & Hillyard, 1980). We recorded EEG while participants read for meaning sentences with five types of endings: expected words, unexpected words, expected acronyms, unexpected acronyms, and meaningless illegal strings of letters. If, as we propose, the processing of acronyms for meaning is computationally similar to that for words, then we should expect to see equivalent N400 expectancy effects (smaller N400 responses to expected as compared with unexpected sentence completions) for these two stimulus classes. Furthermore, a comparison of the responses to the three classes of unexpected items (words and acronyms in inappropriate sentence contexts and illegal strings, which are always unexpected) will provide additional data about the roles of meaningfulness and lexical density in eliciting N400 activity.

Methods

Participants

Data were analyzed from 16 participants (11 female, age range 18–29, mean age 21.9). All were right-handed, monolingual speakers of English with normal or corrected-to-normal vision and no history of neurological disease or defect. Participants were graduate or undergraduate students at the University of Illinois. The experimental protocol was approved by the Internal Review Board of the University of Illinois, and all participants were compensated with money or course credit.

Stimuli

The stimuli were composed of sentence frames with five different ending types: expected words, unexpected words, expected acronyms, unexpected acronyms, and meaningless illegal strings. Illustrative examples of all five stimulus types along with sentence-level characteristics are displayed in Table 1. The number of acronyms that could be used in the study was limited by the need for a high degree of experimental control, as acronyms had to be orthographically illegal, well known by participants, and felicitously used as a sentence ending, and we had to be able to match cloze probability and plausibility across acronym and word completions. In the end, 46 acronyms met all the criteria. Thus, each participant received 23 items each of expected and unexpected sentence-final acronyms and expected and unexpected sentence-final words and 46 sentence-final illegal strings. There were twice as many sentences ending with illegal strings as any other category so that the proportions of familiar, legal endings, familiar, illegal endings, and unfamiliar, illegal endings would be identical. Because N400 anomaly effects tend to be large (at least 3–5 μV), the smaller number of trials was not expected to affect our ability to see effects in individual participants.

Acronyms were composed of either all consonants or all vowels. These were considered familiar on the basis of data from a large-scale ($N = 236$) norming study (Laszlo & Federmeier, 2004) and also on the basis of individual questionnaires assessing acronym knowledge administered after EEG collection. Data collected for sentences ending in acronyms with which individual participants were unfamiliar were omitted from analysis on a participant-by-participant basis, ensuring that all acronyms included in analysis were, in fact, known by our specific participant set. Illegal strings were also composed of either all consonants or all vowels. No illegal string used as a sentence completion was ever identified as being a meaningful string in the acronym norming study. Table 2 includes examples as well as lexical characteristics of all three item types.

To ensure a high level of ecological validity, sentences with acronym completions were drawn from a set that was generated by undergraduates at the University of Illinois in the acronym norming study (participants in that study were asked to write sentences to illustrate the meaning of acronyms with which they were familiar; Laszlo & Federmeier, 2004). These sentences, along with sentences designed to elicit word completions, were normed for cloze probability and plausibility in separate sessions, each with 20 participants drawn from the same participant pool at the University of Illinois from which the participants in the ERP study were ultimately drawn. In the following description of the results of these norming studies, all *t* tests are two-tailed, two-sample tests with Satterthwaite's approximation applied to the degrees of freedom to account for an assumption of unequal variance between the samples.

For cloze probability norming, participants were presented with sentence frames missing their final word or acronym. They were asked to provide the "best completion" for the sentence and to then give two additional, plausible sentence endings. Participants were told that completions should be single words or acronyms and were encouraged to include at least one acronym completion in the set of three whenever possible. Cloze probability of a particular item in a given frame was defined as the proportion of participants who provided that item as the first (best) completion for that frame. Sentential constraint was defined as the cloze probability of the most frequent first completion for a sentence frame. The final set of acronym and word sentences were chosen from the normed set such that sentential constraint and cloze probability could be matched across the two stimulus categories. Acronym and word sentences presented in the ERP experiment did not differ from each other in constraint, $t(77.9) = 0.31$, $p = .76$, or cloze probability of the final items actually presented, $t(75.9) = -0.88$, $p = .38$. Cloze and constraint values are not identical because in a few cases the items presented in the ERP experiment were not the most frequent completions for a given sentence frame.

In the plausibility norming, participants were asked to indicate on a scale of 1–7 (1 = *makes no sense*, 7 = *makes perfect sense*) "how much sense" each sentence made. In the plausibility study, half of the participants saw a given word or acronym sentence frame with its unexpected ending and half of the participants saw that same frame with its expected ending. All participants saw the illegal string sentence frames with their (unexpected) illegal string endings. The plausibility of expected words and expected acronyms in their sentence frames did not differ significantly, $t(56.75) = -1.83$, $p = .07$ (there was a trend for expected words to be rated as more plausible), and unexpected acronyms and illegal items also did not differ, $t(81.87) = .59$, $p = .56$. Unexpected words were slightly more plausible in their sentence frames than were unexpected acronyms or illegal strings: unexpected words against unexpected acronyms, $t(60.63) = -2.9$, $p = .0048$; against illegal strings, $t(53.33) = -3.33$, $p = .002$.

For the ERP experiment, sentences were divided into randomly ordered lists such that for each of the word and acronym sentence frames, half of participants saw that frame with an expected ending and half saw it with an unexpected ending. Thus every participant saw every frame exactly one time, and across participants every acronym and word frame was presented an equal number of times with an expected or unexpected ending. Correspondingly, across participants each acronym and word was presented an equal number of times as an expected or unexpected completion.

Procedure

Once EEG setup was complete, participants were seated in a comfortable chair 100 cm away from the computer monitor on which stimuli were presented and given a demonstration of the trial structure. During the demonstration, participants were instructed to minimize eye movements, blinks, and muscle movement except for during a blink interval, which was indicated by the presence of a red cross on the computer screen. Additionally, participants were instructed to keep their eyes on a fixation arrow in the center of the screen as much as possible throughout the experiment. Finally, participants were informed that they would be given a memory test for the sentences that they were about to see, and that the best strategy they could use to help them remember the sentences was to try to vividly imagine what was going on in each sentence. Although the results of the memory test were not of interest for the experimental questions in the current study, this task was included as a means of motivating participants to attend carefully to the meaning of the experimental sentences. No response was required from the participants for any event during EEG collection. After the demonstration, participants engaged in a practice block of sentences with characteristics similar to those employed in the experiment in order to familiarize themselves with the pace and structure of the task.

In both the practice and the experiment proper, a fixation arrow was continuously present in the center of the screen. Each sentence was preceded by a 1000-ms-long warning that a sentence was about to begin followed by a blank screen presented for a randomly jittered duration of between 500 and 1000 ms. Then, words appeared one at a time in the center of the screen. Each word appeared for 250 ms and was followed for 250 ms with a blank screen, except for the final word in each sentence, which was followed by a 1000-ms-long blank screen and then a 2000-ms-long blink interval during which a red fixation cross was displayed and participants were encouraged to blink or move their eyes. All stimuli were presented in all capital letters in 24-point font in white on the black background of a CRT computer monitor at resolution of 640 × 480, with the exceptions of the pretrial warning and blink cross, which were presented in red.

Electroencephalogram (EEG) Recording

EEG was recorded from 26 Ag/AgCl electrodes embedded in an electrode cap and arranged on the scalp in a geodesic array. All EEG electrodes were referenced online to the left mastoid process and then digitally re-referenced off-line to the average of the left and right mastoids. The electrooculogram (EOG) was recorded using a bipolar montage of electrodes placed at the outer canthi of the left and right eyes; blinks were monitored using an electrode at the suborbital ridge. EEG and EOG were recorded with a bandpass of 0.02 to 100 Hz and sampled at a rate of 250 Hz with a gain of 10,000×. All electrode impedances were kept strictly below 2 kΩ. Event-related potentials were computed at each electrode time-locked to the onset of the sentence final words in each of the five critical sentence types. Average ERPs contain a 100-ms prestimulus baseline and continue for 920 ms after stimulus onset. Measurement of ERP peak latency and mean amplitude was conducted on data digitally filtered off-line with a bandpass of 0.2 to 20 Hz. Trials containing eye movement or drift artifacts were rejected with a threshold individualized to each participant by inspection of that participant's raw waveforms, and blinks were corrected using a procedure described by Dale (1994). Artifact rejection resulted in an average loss of 3% of trials per participant.

Results

Behavioral Data

Mean *d′*, for performance in the subsequent memory test was 2.27. A two-tailed, one-sample *t* test against the null hypothesis that the mean of the *d′* distribution was zero was reliable, $t(15) = 6.77$, $p < .0001$, indicating that participants were able to discriminate old from new sentences.

Electrophysiological Data

The N400 was measured by computing mean amplitudes of grand average waveforms elicited by all five ending types in a 250–450-ms poststimulus-onset epoch, relative to a 100-ms prestimulus baseline. In what follows, main effects of electrode site are not reported, as they were of no theoretical significance. All statistical tests are repeated measures analyses of variance (ANOVAs), with degrees of freedom adjusted by the Greenhouse–Geisser correction for violation of the assumption of sphericity.

An omnibus analysis of mean amplitudes in the 250–450-ms window with factors of item type (word, acronym), expectancy (expected, unexpected), and electrode site revealed main effects of item type, $F(1,15) = 58.0$, $p < .0001$, and expectancy, $F(1,15) = 16.17$, $p = .001$. The main effect of item type was obtained because acronym endings elicit overall more positive waveforms than do word endings in this epoch. The main effect of expectancy manifested in the waveforms as a marked positivity for expected relative to unexpected endings. Figure 1 shows the expectancy effect for acronym endings over all 26 scalp channels. Follow-up pairwise comparisons confirmed that there was an effect of expectancy at both the acronym and word levels of item type: for acronyms, $F(1,15) = 7.57$, $p = .015$; for words, $F(1,15) = 12.99$, $p = .003$. There were also significant interactions of item type with electrode, $F(25,275) = 9.8$, $\varepsilon = .09$, $p = .0004$, and expectancy with electrode, $F(25,375) = 6.34$, $\varepsilon = .17$, $p = .0002$, as both the effect of item type and the effect of expectancy were largest over central-parietal channels. However, there was no interaction between expectancy and item type, $F(1,15) = 0.01$, indicating that the effect of expectancy did not differ in magnitude between the two item types. Figure 2 displays ERPs elicited by expected and unexpected words and acronyms side by side at a representative middle parietal (MiPa) channel. The three-way interaction was also not reliable, $F(25,375) = 1.05$.

To further examine and compare the effects of expectancy on the two item types, difference waves for both word and acronym endings were calculated by subtracting the waveforms elicited by expected endings of an item type from waveforms elicited by unexpected endings of the same item type on a point-by-point basis. The peak amplitudes of the word and acronym expectancy effect difference waves over the middle parietal channel in the 250–450-ms epoch were 3.79 μV and 3.65 μV, respectively. A distributional analysis of the expectancy effects elicited by both item types in the 250–450-ms window was performed using a repeated measures ANOVA that included a factor of ending type (word or nonword), and then considered 16 scalp channels that could be divided into factors of hemisphere (right or left scalp sites), laterality (lateral or medial scalp sites), and anteriority (prefrontal, frontal, central-parietal, or occipital scalp sites). This distributional analysis revealed no significant main effect of stimulus type, $F(1,15) = 0.01$, or any interactions of stimulus type with any distributional factor (all *F*s < 2.0). An analysis of the peak latency of the expectancy effect conducted over the middle parietal channel revealed no effect of item type, $F(1,15) = 1.63$. A fractional peak latency analysis of expectancy effect onset latencies was also conducted over the middle parietal channel. In this analysis, the expectancy effect was considered to onset for an item type when the difference wave for that item type reached 20% of its peak amplitude in the 250–450-ms epoch. The fractional peak latency analysis also revealed no effect of item type, $F(1,15) = 0.68$.

The main effect of item type in the omnibus analysis was obtained because acronym endings appear to elicit overall more positive waveforms in the N400 epoch than do word endings. To further characterize the differences in the waveforms elicited by different item types, we compared the mean amplitude of unexpected words, unexpected acronyms, and illegal strings of letters (which were, by definition, unexpected) in the 250–450-ms time window. Illegal string endings were similar in orthographic irregularity and small neighborhood density to our acronym endings but devoid of semantics. A first-pass ANOVA with factors of ending type (unexpected word, unexpected acronym, illegal string) and electrode indicated a significant main effect of ending type, $F(2,30) = 30.81$, $\varepsilon = .89$, $p < .0001$, and a significant interaction of ending type and electrode, $F(50,750) = 10.40$, $\varepsilon = .08$, $p < .0001$. As can be observed in Figure 3, the main effect of ending type is principally driven by a larger negativity for unexpected words than unexpected acronyms or illegal strings in this epoch. The interaction of ending type and electrode is obtained as this enhanced negativity for unexpected words is largest over centro-parietal channels. Follow-up pairwise comparisons indicated that, although the waveforms elicited by unexpected words were more negative than those elicited by unexpected acronyms, $F(1,15) = 31.62$, $p < .0001$, or illegal strings, $F(1,15) = 74.08$, $p < .0001$, the waveforms elicited by unexpected acronyms and illegal strings did not differ from one other in this epoch, $F(1,15) = 0.54$.

Exploratory analyses identical to that conducted in the 250–450-ms epoch with factors of item type (word, acronym), expectancy (expected, unexpected), and electrode were additionally conducted in both the pre- and post-N400 windows. In the early (0–250-ms) window, there were no main effects of item type or expectancy and no interactions of those factors with any other factor (all *F*s < 2.0). In the late (450–750-ms) window, there was a reliable main effect of item type, $F(1,15) = 47.12$, $p < .0001$, as well as a reliable interaction of ending type with electrode, $F(25,375) = 4.10$, $\varepsilon = .14$, $p = .01$. The main effect of item type is obtained because words continue to elicit more negative ERPs than do acronyms or strings in this epoch; as in the N400 time window, this greater negativity for words is more pronounced over medial and parietal channels. There is no main effect of expectancy in this window, $F(1,15) = 0.07$, nor are there any interactions between expectancy and any other factor (all *F*s < 2.5). Thus, although waveforms elicited by unexpected words appear slightly more positive than those elicited by expected words in this epoch (see Figure 2), that tendency is not statistically reliable.

Discussion

We presented participants with sentence frames that had expected or unexpected endings that were either orthographically regular and familiar (words), orthographically illegal and familiar (acronyms), or illegal and unfamiliar (consonant or vowel strings.) Based on prior findings (Laszlo & Federmeier, 2007b) suggesting that even orthographically illegal items can elicit N400 repetition effects so long as they are familiar, we predicted that, like expected words, expected acronyms would elicit N400s of smaller magnitude than unexpected ones. This prediction was confirmed. Familiar acronyms that were sensible and expected completions of their sentence frames elicited reduced N400 amplitudes compared to familiar acronyms that were implausible completions. Indeed, the magnitude of this facilitation, as well as the scalp distribution and timing of the congruency effect, was indistinguishable from that observed for similarly plausible and expected word endings. Thus, whether they are presented in a list or in a sentence context, familiar strings that cannot be pronounced (or even approximated) by English spelling-to-sound rules nevertheless elicit clear N400 responses, which are similar to those elicited by words in their timing, distribution, and sensitivity to factors such as repetition and congruency. This pattern of findings provides strong evidence that orthographically illegal stimuli make contact with semantics in a manner similar to orthographically legal stimuli, contrary to the predictions of dual-process models of reading. Of course, there is the possibility that these results for English would not generalize to languages with more transparent orthography-to-phonology mappings. Adherents of both single- (Harm & Seidenberg, 2004) and multi-route (Ziegler, Perry, & Coltheart, 2000) models have acknowledged that an individual's language-processing system may load more heavily on direct orthography to semantics computations or mediated orthography-phonology-semantics computations depending on the orthographic transparency of that individual's language. It could conceivably be the case that, in a language more transparent than English, where phonological mediation can be successful at producing a correct phonological representation of orthographic inputs a higher proportion of the time, less dominance for direct access to semantics might be observed than was observed in our studies.

One difference between the response to familiar acronyms and that to words is that acronyms elicit globally more positive responses in the N400 time window. This finding in the present study for acronyms in sentence contexts replicates that seen in Laszlo and Federmeier (2007b) for acronyms in word lists, although responses to all stimulus classes were more positive in word lists than in sentences. Greater positivity to acronyms than to words is consistent with the fact that decreased lexical density has been associated with smaller N400 amplitudes (Holcomb et al., 2002), as acronyms are lower in lexical density than at least the words used in these studies. If lexical density is driving the baseline size of the N400, then responses to our illegal strings might be expected to pattern with responses to the acronyms, as these stimulus classes were matched for lexical density. Indeed, our prior study (Laszlo & Federmeier, 2007b) had shown that, on single presentation, the ERPs elicited by familiar illegal acronyms were indistinguishable from those elicited by meaningless illegal strings in the N400 epoch, despite the fact that acronyms elicited N400 repetition effects whereas illegal strings did not. Again, this finding replicates in the present study for these same stimulus classes presented in sentences: Mean amplitudes in the N400 time window were statistically indistinguishable for the unfamiliar illegal strings and the familiar acronyms (when unexpected and hence matched in congruity with the illegal strings, which were never expected). Thus, irrespective of familiarity or regularity, lexical density seems to be an important determining factor for N400 amplitudes in the absence of other factors (e.g., repetition, congruency) that are known to alter N400 amplitude.

What is striking about the response to the illegal strings in this study is that they manifest what would appear to be a clear N400 component. Prior studies using unfamiliar, illegal strings had always presented these items in a list context, where they elicited a broad positivity (Laszlo & Federmeier, 2007b; Rugg & Nagy 1987). Based on this morphology, it had been suggested (e.g., Deacon et al., 2004) that illegal strings fail to elicit N400 activity altogether and, hence, that written input must be somehow filtered, with some, but not all, strings inducing the processes indexed by the N400. In a list context, first presentations of illegal but familiar acronyms also elicit broad positivity, with no clear N400 peak (Laszlo & Federmeier, 2007b); however, subsequent presentations of these items lead to clear N400 repetition effects that are indistinguishable from those to words, raising the question of whether it is appropriate to determine the presence or absence of N400 activity from waveform morphology alone. In fact, in the present sentence processing study, where overall responses in the N400 time window are less positive, illegal items are associated with what would appear to be a clear, negative-going peak around 365 ms. This component peak has the same size and distribution as the peak elicited by the length and density-matched unexpected acronyms, which, in turn, was clearly modulated by expectancy in the same manner as the well-studied N400 congruency effect for words. Thus, it would seem that even meaningless, orthographically illegal, low lexical density items can and do elicit N400s, at least when presented in the context of words and other familiar strings. This furthermore suggests that it may have been premature to conclude that a filter of any kind is applied to written input before N400 processing can take place.

We propose that, instead of a filter on incoming written input that dictates which inputs can be processed for semantics and which cannot, all letter strings may automatically initiate attempts at semantic access. However, such attempts are not necessarily always successful. Illegal strings presented in word lists are unlikely to elicit stable, reproducible activity at lexico-semantic levels of representation. This is probably why they do not manifest N400 repetition effects: There is no residual activation of any representation to confer a benefit when that same string is presented a second time. In contrast, words, pseudowords, and familiar acronyms all benefit from repetition in word lists because all three are either represented themselves (words and acronyms) or are highly similar to items that are represented (words and pseudowords, which generally have at least one, and often many, close lexical neighbors). Supporting evidence for the claim that being semantically represented and being similar to represented items are separable properties that are both important to lexical-semantic access is found in a behavioral result from our acronym superiority effect study (Laszlo & Federmeier, 2007a), where we observed that the superiority effects enjoyed by words (which are both represented and similar to other represented items) were larger than those enjoyed by pseudowords (which are only similar to represented items) or acronyms (which are represented themselves but not similar to other represented items).

The situation for an unfamiliar, illegal string presented at the end of a sentence may be somewhat different. Whereas word lists provide little supporting contextual information to the semantic access processes engaged by each incoming item, in a sentence context every word prior to the sentence final stimulus is building up an increasingly coherent message-level semantics (e.g., Van Petten & Kutas, 1990). Thus, although an illegal string may not itself elicit stable activity in lexico-semantic networks, in the context of a sentence, such a string may be able to inherit semantic content from the message-level information that has accrued. Indeed, this would be a useful mechanism for a language processing system that also learns, because unfamiliar—and, in the case of unknown acronyms, orthographically illegal—strings *are* sometimes encountered during normal language comprehension. If input is filtered at fairly early stages of stimulus processing, as has sometimes been hypothesized (e.g., Deacon et al., 2004), then such items will never be processed for meaning and will thus be quite difficult to learn through exposure alone. In contrast, if automatic attempts at lexical access result in novel strings becoming associated with the semantics of the context in which they occur, then learning of new wordform-to-meaning mappings can occur in the course of routine language experience. One test of this proposal would be to determine whether illegal strings elicit N400 repetition effects when they are repeated in a sentence or connected text, as words do (Van Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991).

Conclusion

The argument that there is no filter on incoming written language, such that identical attempts at meaning access are made for every orthographic stimulus encountered by the language processing system, is more consistent with computationally homogenous models of visual word recognition from the connectionist tradition than with the dual-process models of the neuropsychological tradition. In single-process models, all inputs are subjected to computationally identical processing, regardless of their lexical characteristics; the same computations would be applied to a word, a pseudoword, an acronym, or an illegal string input. The output of a single-process model exposed to those categories of inputs will not always be identical, but the processing applied to them would be. On this view, if the N400 reflects activity in a lexico-semantic network, then that activity should be observed for all orthographic inputs, irrespective of familiarity or regularity. The amount of that activity (i.e., the amplitude of the N400) would then be a reflection of variables such as the breadth or richness of the activity engendered by the stimulus (e.g., larger for stimuli associated with denser lexical neighborhoods) and the extent to which there is residual activation of the representations in question from factors such as prior exposure or contextual preactivation. Indeed, this is precisely the pattern we have observed. This pattern, however, is hard to reconcile with dual-process models, which propose that different computations (occurring with differing time courses in separable brain areas) are performed depending upon the outcome of filters that at least implicitly assess the familiarity or regularity of incoming orthographic stimuli.

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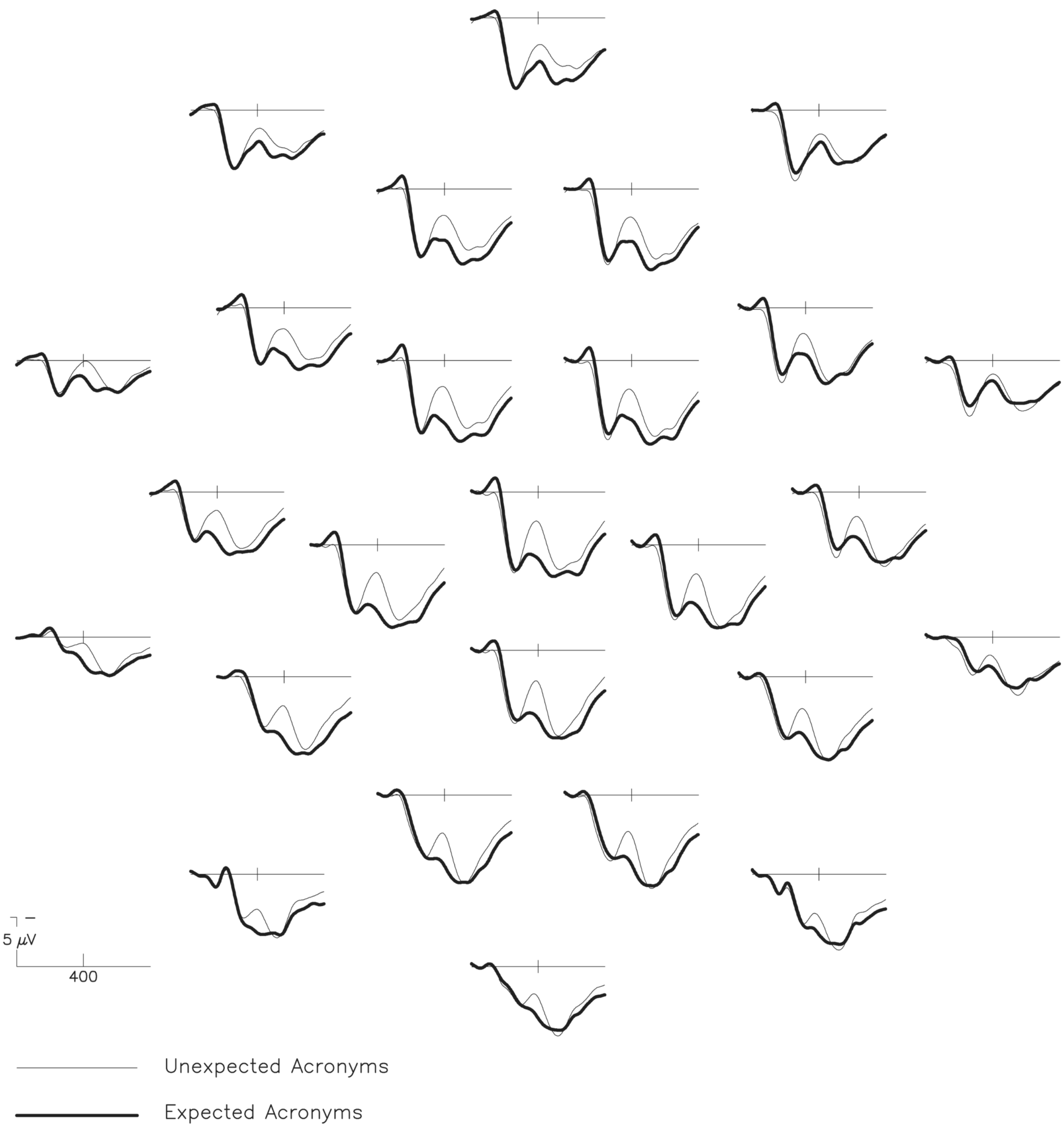

Figure 1.
Grand average waveforms elicited by unexpected and expected sentence-final acronyms at all 26 scalp channels. Expected acronym ERPs are notably more positive in the 250–450-ms N400 window than are unexpected acronym ERPs.

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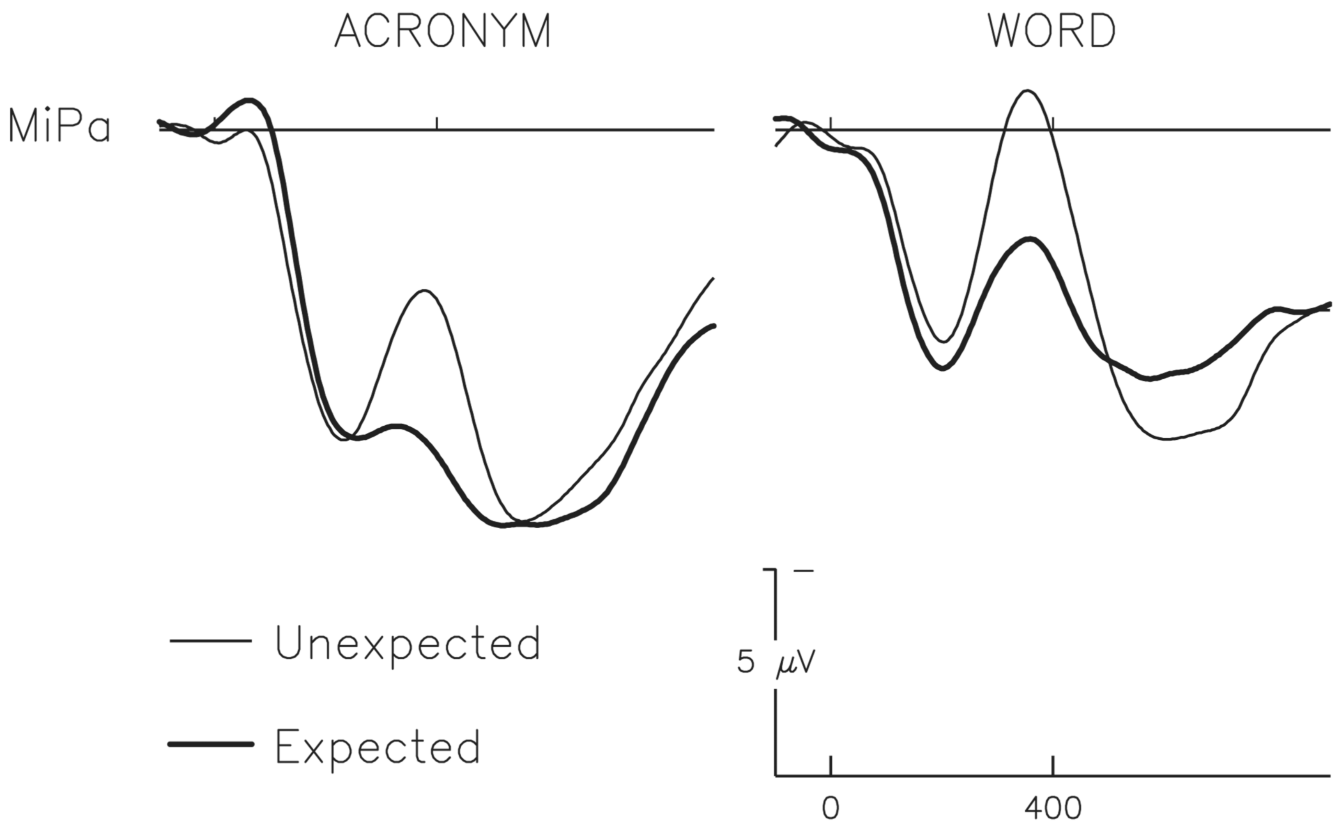

Figure 2.
Grand average ERPs elicited to unexpected and expected acronyms and words at the middle parietal channel. Response to expected endings is more positive in the N400 window for both item types. The apparent positivity for unexpected word endings is not statistically reliable in the post-N400 window.

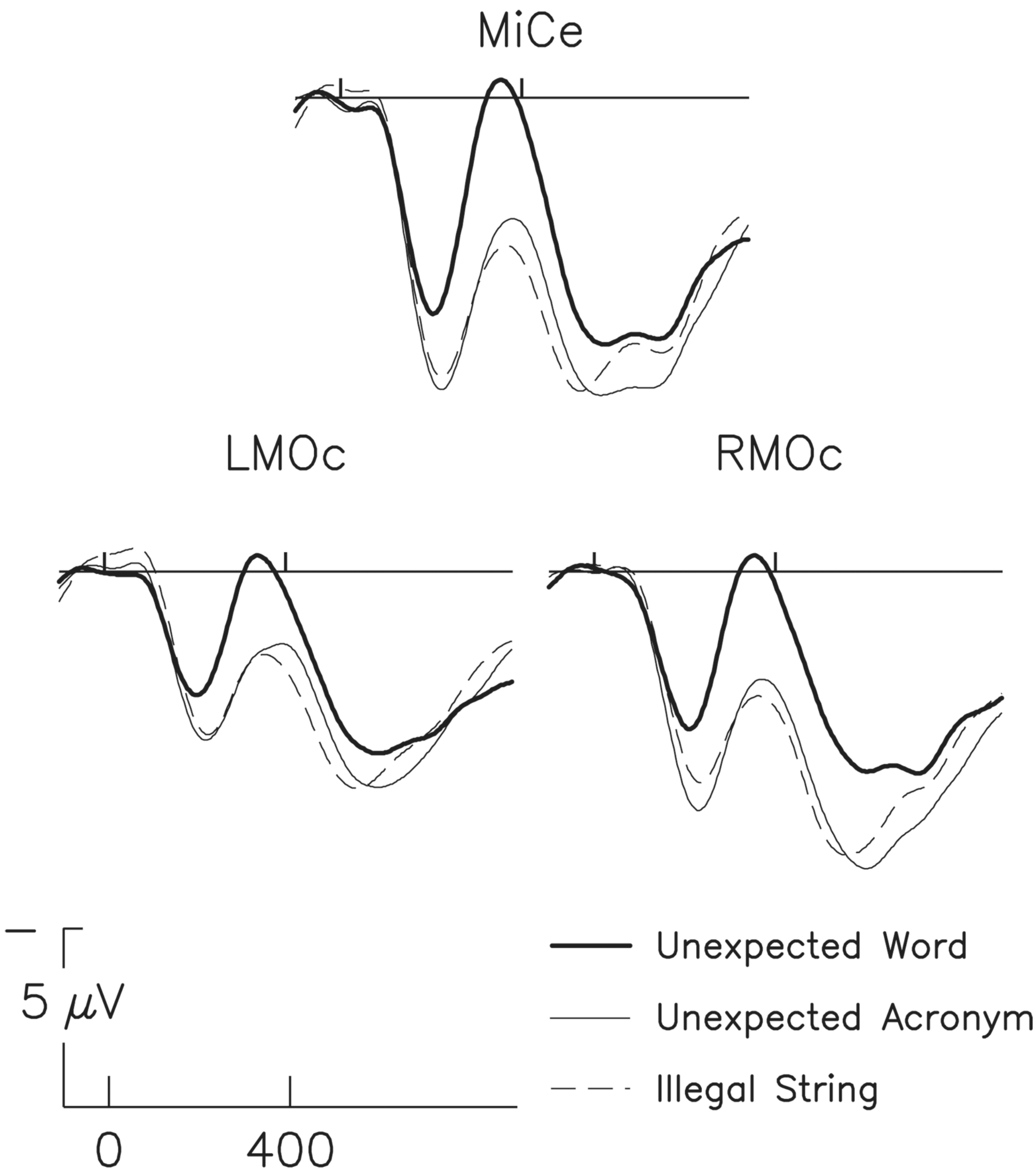

Figure 3.
Grand average waveforms elicited by unexpected words, unexpected acronyms, and illegal strings at a representative selection of central parietal channels; the unexpected acronym and illegal string categories of sentence ending type are similar in their orthographic illegality and their low lexical density. In the 250–450-ms N400 window, the ERPs to words are reliably more negative than those to unexpected acronyms or illegal strings whereas the responses to unexpected acronyms and illegal strings are indistinguishable.

Table 1

Representative Examples and Sentence-Level Characteristics of All Five Stimulus Categories

Sentence type	Example	Cloze probability	Plausibility[a]
Word: expected ending	SHE FELT DINNER WOULD NOT BE COMPLETE UNLESS SHE MADE DESSERT.	0.42 (σ = 0.17)	6.9 (σ = 0.21)
Word: unexpected ending	SHE FELT DINNER WOULD NOT BE COMPLETE UNLESS SHE MADE BUGS.	0	2.3 (σ = 1.43)
Acronym: expected ending	BECAUSE I WORK AS A LIFEGUARD, I NEED TO KNOW CPR.	0.38 (σ = 0.28)	6.7 (σ = 0.59)
Acronym: unexpected ending	BECAUSE I WORK AS A LIFEGUARD, I NEED TO KNOW HDTV.	0	1.6 (σ = 0.60)
Illegal string: unexpected ending	HE HAS STARTED BIKING TO WORK INSTEAD OF DRIVING HIS RCM.	0[b]	1.5 (σ = 0.44)

[a]1 = least plausible, 7 = most plausible.

[b]Value collected in a previous norming study with the same sentence frames at the University of California, San Diego.

Table 2

Representative Examples and Lexical Characteristics of All Three Sentence-Final Item Types

Item type	Example	Length	Written probability	Lexical density
Word	DESSERT	4.85	1.8 × 10E-4	4.43
Acronym	CPR	3.17	2.8 × 10E-6	1.04
Illegal string	RCM	3.17	1.1 × 10E-3	1.39

Note: Written probability is defined as the number of times an item appeared in its corpus divided by the number of items in that corpus. Written frequency of an illegal string was defined as the sum of the number of times every word containing that string appeared in the Kuçera-Francis (1967) corpus. Lexical density of each item was defined as the number of words that could be created with single letter substitution, and was obtained from the Washington University Speech and Hearing Lab online database (http://128.252.27.56/Neighborhood/NeighborHome.asp; accessed 2006). By design, acronyms and illegal strings were exactly matched in length and did not reliably differ in lexical density. Illegal string written probability was, again by design, higher than that for acronyms in order to preclude the possibility that written probability, and not semantic familiarity per se, was driving any difference observed between acronym and illegal string waveforms.