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FEATURE ARTICLE

A Brain Potential Whose Latency Indexes the Length and Frequency of Words

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A Brain Potential Whose Latency Indexes the Length and Frequency of Words

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Abstract

ERPs were recorded from 24 undergraduates in an investigation of the effects of length, frequency, and grammatical class on the brain's response to words during sentence reading. Our results indicate that the combined length and frequency of a word are indexed by the latency of a negative peak maximal over left anterior regions of the scalp that we call the Lexical Processing Negativity or LPN; the form of this relationship mirrors that between these same lexical factors and reaction times. The length-frequency effect on the LPN accounts for some of the known electrophysiological differences between open class (content) and closed class (function) words. The LPN also helps bridge a perceived gap between reaction time and electrophysiological data as measures of cognitive processes in visual word recognition.

While the question of how language processing is subserved by the brain has been asked concerning many levels of linguistic analysis, the bulk of the research has dealt with the processing of single words. In particular, the focus has been on when and where in the brain lexical access[1] occurs, and whether these processes differ for words of different syntactic categories. With few exceptions, studies of lexical access have relied on manual or verbal reaction times (RTs) or eye movement gaze durations as the dependent variable. In reading studies, these have revealed that encoding and lexical access times are in large part a function of a word's length in letters and its frequency of daily usage; longer words take more time to process than shorter words, and rare words more time than common words (see, e.g., Just & Carpenter, 1980). More specifically, regression analyses suggest that each character adds about 30 msec to the expected gaze duration on a word, while each (common) log unit of frequency subtracts about the same amount (Thibadeau, Just & Carpenter, 1983). Indeed, extremely short, common words like “the” and “of” are often not directly fixated at all. Most unfixated items tend to be so-called “function words” (e.g., articles, conjunctions, prepositions, auxiliaries) which are generally shorter, more frequent, and more predictable from context than “content words”.

Function and content words (e.g., verbs, nouns, adjectives and some adverbs) also differ in that while new content words can be freely coined, the set of function words is essentially “closed” to new members. Thus, content words are often called “Open Class” words while function words are called “Closed Class” words. It has been suggested that closed class items, which carry information primarily about syntactic structure, and open class words, which carry primarily semantic information, may be processed by functionally and anatomically distinct brain areas (e.g., Swinney, Zurif, & Cutler, 1980). In support of this hypothesis, some researchers have reported that frequency effects are not the same for normal subjects and Broca's aphasics, who typically show disproportionately greater difficulties both in producing and comprehending closed than open class items. Specifically, normal subjects show frequency effects in their RTs to open class words only, whereas Broca's aphasics show frequency effects to both open and closed class words (Bradley, Garrett, & Zurif 1980). However, this pattern of results for normal subjects has not been replicated consistently, and it has been suggested that technical problems in estimating frequency effects on very rapid RTs may render this issue unamenable to resolution using behavioral data alone (Gordon & Caramazza, 1985).

In contrast to the robust findings in the reaction time literature, differences in the event-related brain potentials (ERPs) to words due to word length and frequency have been subtle, while differences between open and closed class items have been quite large (e. g., Van Petten and Kutas, 1991; Neville, Mills and Lawson 1992). The largest ERP difference appears to be in the amplitude of the N400 responses. Virtually all open class words in sentence contexts generate an N400 whose amplitude depends on a variety of factors including cloze probability (Kutas & Hillyard, 1984), repetition (Van Petten et al., 1991), and frequency to a limited extent (i. e. only for the first few open class words in sentences; Van Petten & Kutas, 1991). By contrast, closed class words typically do not generate large, if any, N400s (but see King & Kutas, 1995b, for a notable exception and Kluender & Kutas 1993 for discussion). Recently, Neville, Mills, and Lawson (1992) have claimed that the ERPs to closed class words differ from those to open class words not only by the absence of an N400 but also by the presence a negativity at the left anterior scalp around 280 msec (i.e. the N280). They concluded that the N280 was a qualitative sign of a word class effect because it was not elicited by open class words regardless of their

[1]We use the term lexical access to refer to the execution of the process(es) that brings a word's semantic meaning, syntactic category, and possibly other information into working memory from long term memory representations during a language comprehension task.

length or frequency. These facts combined with its suggestive scalp localization over left anterior sites has fueled speculation that the N280 is generated in or near the classical Broca's area and has been offered as support for “...the activation of different neural systems that are organized to process the different kinds of linguistic information that these word classes provide” (Neville et al., 1992).[2] Perhaps in part because of temporal overlap with the N400, much less attention has been given to the presence of a similar, albeit slightly later, negative peak at left anterior sites for open class words as well (i.e. N410) (e.g., Neville, Kutas, Chesney and Schmidt, 1986).[3]

The possibility that the left anterior negativities generated by open class and closed class words are identical has not yet been investigated directly, although it is reasonable to hypothesize that they both index a process whose dynamic timing is affected by lexical class or correlated lexical factors such as length and frequency.[4] If the difference in latency is strictly categorical, and related to fundamental differences between closed and open class items, then the latencies of members within the two classes might be fixed, unrelated to lexical factors, and not comparable between classes. On the other hand, if both the N280 and the N410 partially index processes affected by lexical factors, then the duration of these processes might be reflected in the latency of this left anterior negativity in a systematic fashion. Specifically, its latency, both within and between lexical classes, may be a function of lexical factors such as length and frequency which have large down-stream effects on reaction times.[5]

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[2]Statements such as this one presuppose a strong association between Broca’s area and receptive grammatical processing that is based on the classical English language aphasia literature. More recent and cross-linguistic research sheds doubt on the strength of this association (see, e. g., Bates, Wulfeck, and MacWhinney, 1991).

[3]The original experiment defining the N410 (Neville et al., 1986) used text presented vertically in either the left or right visual field; with normal text, the latency of the N410 generally decreases to, for instance, 330 msec in the work of Nobre and McCarthy (1994).

[4]To date, differences in the ERPs elicited by words which are due to frequency, length, and lexical class have been observed primarily as modulations in amplitude (or presence) of certain components rather than in their latency. This relative lack of latency effects is worth noting as one might expect that ERP data would be especially useful in providing information about the pre-response chronometry of cognitive events.

[5]Individual ERP peaks are undoubtedly more complex than we have suggested since they often reflect the activity of multiple neural generators operating simultaneously. Thus, shifts in the latency of a particular peak might still be taken as evidence that some of generators active in response to a stimulus are altered in their timing.

Method

Subjects and Materials

Twenty-four right-handed, normal, native English monolingual UCSD students (12 women) between 18 and 27 years of age participated in the study after giving their informed consent in compliance with university procedures, and received $5.00 an hour for their time. The materials included 288 sentences, of which 72 were the critical materials for another study (King & Kutas, in press) and the other 216 were filler sentences of various syntactic structures. The results reported here are based on the ERPs to the single words of the filler sentences. These words were sorted into 10 broad classes based on their syntactic features. Open Class types included *Nouns*, *Verbs,* and *Adjectives*; Closed Class types were *Infinitival “To”*, *Definite Articles* (“the”), *Indefinite Articles* (“a” or “an”), *Noun Phrase Prepositions* (e.g. “of”), *Verb Phrase Prepositions* (e.g. “for”), *Conjunctions*, and forms of the verb *To Be* (e.g. “was”, “is”). For each class, the mean length in letters for the members was computed, as was mean “scarcity”. Scarcity was calculated as the common log of each word's frequency in the Francis and Kucera corpus lexicon (1982) subtracted from 6 (the highest possible log frequency in a 1 million word corpus). This transformation yields a variable, like word length, that is positively (rather than negatively) correlated with reaction time on most tasks.

Procedure

Subjects read sentences presented one word at a time in the center of a CRT while their electroencephalogram (EEG) was recorded. Words were presented for a duration of 200 msec with a 500 msec word onset asynchrony. Subjects were instructed to read each sentence knowing that a True/False comprehension probe would follow approximately half the sentences. ERPs were recorded from 6 pairs of lateral electrodes on an Electro-Cap and from electrodes placed on the left and right mastoids. All electrodes were referenced to a noncephalic lead derived from an electrode placed at the sterno-clavicular junction and over the seventh cervical vertebra both fed through a potentiometer adjusted to reduce cardiac artifact. The electrodes covered both standard 10-20 sites (F7, F8, T5, T6, O1, O2), one pair approximately over left and right primary auditory cortex, and one electrode each over Broca's area, Wernicke's Area, and the two locations over the right hemisphere analogous to these language areas. The electrode site that is the primary focus of this paper is F7, which lies over the lateral aspect of the left anterior scalp, and will be henceforth referred to as Left Frontal. Subjects' EEG was digitized on-line with a sampling rate of 250 Hz

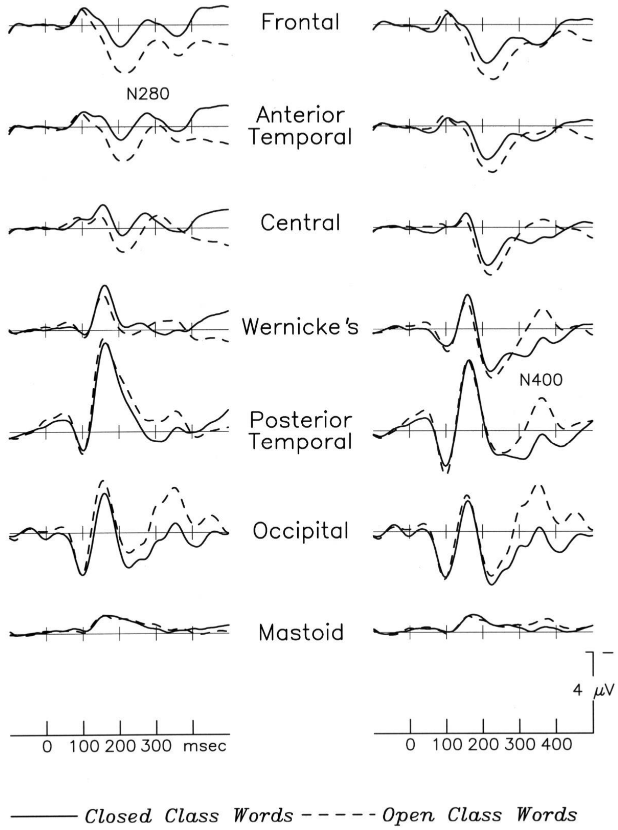

Figure 1. Grand average ERPs (n=24) from 14 electrode sites for the Open Class (solid line) and Closed Class words considered in this study. The left hemisphere is plotted on the left, and negative voltages are plotted up.

with a time constant of ~8 seconds; eye movement and blink artifacts were rejected off-line prior to averaging. Further details of the experimental procedure are given in King and Kutas (1995b).

Results

Figure 1 contrasts the grand average ERP waveforms for Open and Closed Class words that are the focus of this study.[6] There are clearly several differences between the ERPs to open and closed class words. For example, the ERPs to open class words are characterized by greater negativity between 250 and 500 msec which is larger over right hemisphere sites (the N400), and greater negativity for closed class relative to open class words over left anterior sites. Specifically, the left anterior negativity seen for closed class words includes an early peak with an approximate latency of 280 msec (N280), and a later, broader negativity (N400-700) that overlaps the ERP to the following word (Neville et al. 1992). We should briefly note the N400-700 does seem to be diagnostic of closed class words, but only in sentence contexts; Nobre and McCarthy (1994) detected no such wave in their studies using unstructured word lists. King and Kutas (1995b) and Van Petten and Kutas (1991) have offered explanations of the N400-700 that emphasize the role of closed class words in heading up syntactic constituents in sentential contexts. For open class words, the ERP also includes a negative peak at approximately 315 msec at the left frontal electrode site F7, which is clearly different from the N400 and appears to be identical to the N410 (Neville et al., 1986) and the N330 (Nobre and McCarthy 1994).

Our hypothesis that the N280 and the N315 might reflect a common processing stage predicts that they should vary in latency with lexical factors; Figure 2 shows that the latencies of the N280 and our N315 do seem to vary in the ERPs to the different word types, being earliest (~270 msec) for the shortest and most frequent closed class words such as definite articles, later (~300 msec) for longer and less frequent closed class items such as prepositions commonly used in adverbial phrases, and later still (~ 315 msec) for longer and less frequent open class items such as nouns. Note that some of the other differences between word classes apparent in Figure 2 are statistically reliable, most notably the greater positivity (P2) preceding the N315 elicited by nouns and adjectives; these and other lexical class differences will not be discussed further in this paper.

The real test of our hypothesis, however, is to determine whether the mean latencies of the left

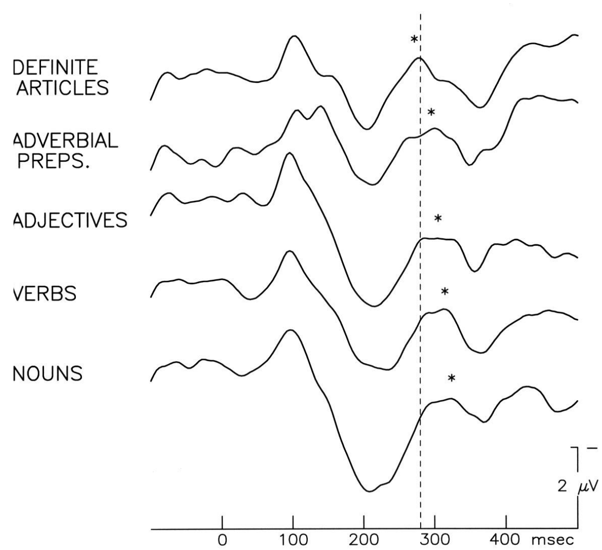

Figure 2. Grand average ERPs (n=24) at the Left Frontal (F7) electrode site for representative word types that are subclasses of the broad Open vs. Closed Class data. Dashed line is at 280 msec; asterisks mark peak latencies for the word types.

[6]Note that the ERPs in this figure are grand means, and that the peak latency of a component in a grand mean is not necessarily a simple function of the mean peak latencies for individual subjects.

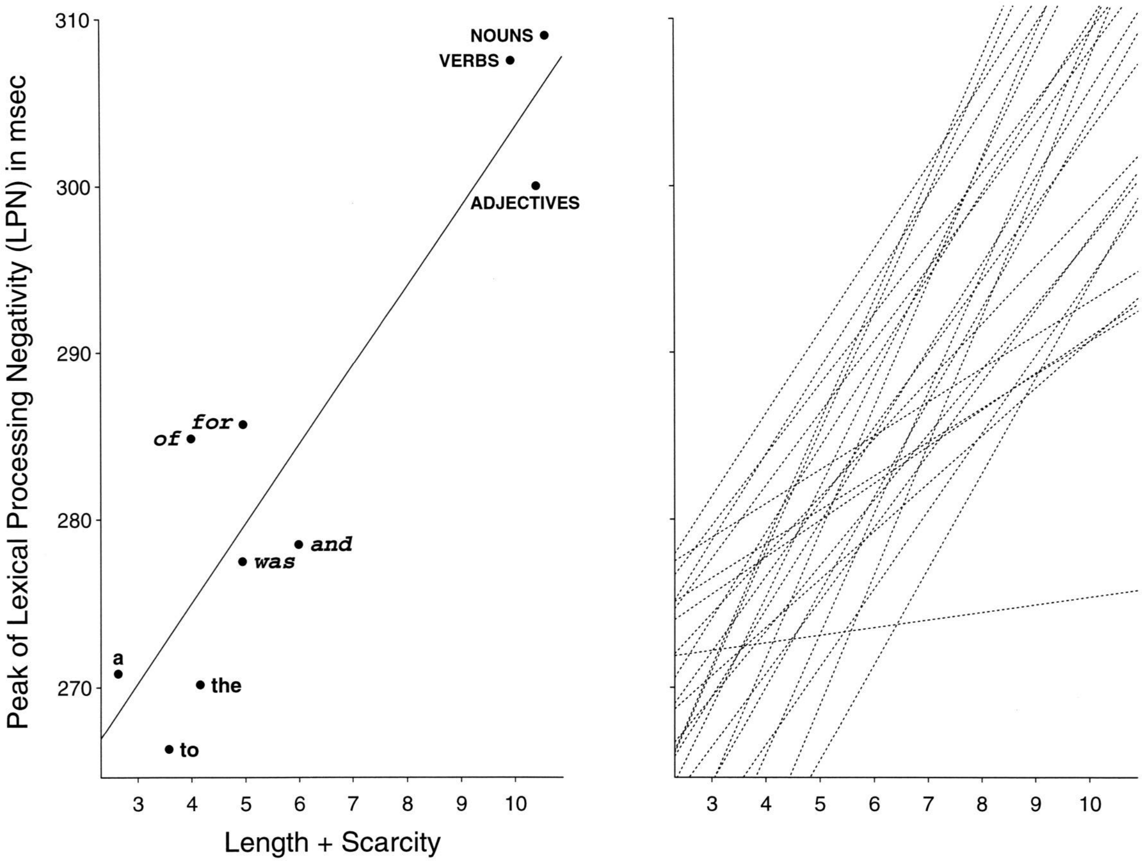

Figure 3. Panel A shows the regression of the Lexical Processing Negativity mean peak latency (in msec.) onto the Length+Scarcity predictor (solid line). Points indicate observations from the 10 lexical types used in the regression, with ALL CAPS used for category labels, oblique lower case used for prototypical category exemplars, and roman lower case used for definitive category exemplars. Panel B shows the superimposed regression lines for all 24 subjects to demonstrate the variability of fits to individual subject data.

frontal negativity to words from a greater variety of Open and Closed Class items can be predicted from their respective lengths and frequencies. To assess this possibility, the peak latency of this negativity for words in each of the ten classes listed in the Methods section was regressed onto the sum of its respective mean length and scarcity.[7] For the mean peak latency data, this resulted in a highly reliable regression ($p < .001$) accounting for 86% of the variance. The left panel of Figure 3 shows both the grand mean latency observations and the best fitting line, whose equation is:

$$P = 256 + 4.8*(L+S)$$

where P is peak latency in milliseconds, L is length in characters and S is scarcity.[8] By way of comparison, Thibadeau, Just and Carpenter (1983) found that length and frequency together accounted for 76% of the variance in gaze duration for (individual) fixated words, collapsed over subjects. It should also be noted that our regression equation is sensible in that it cannot predict a peak latency for this negative wave that would precede the P2 component, due to the location of the intercept. At the same time, this equation does predict latency increases with increasing length or scarcity.[9]

[7]The mean length and frequency variables for our 10 classes were so highly correlated (r(10) = .93) that we could not expect to obtain stable estimates of the parameters in such a regression. Thus, a single predictor was calculated from the sum of these two variables.

[8]Similarly significant regressions were performed for Length alone (P = 258 + 7.5*L, $p < .001$) and Scarcity alone (P = 255 + 11.8*S, $p < .001$. Our choice of the combined variable was motivated primarily from the results of reading studies showing the effect of both variables.

[9]This increase is also found among just closed class items, where the regression equation is P = 261 + 3.6*(L+S). For scarcity alone, the regression is virtually identical in form to that for the whole data set (P = 255 + 12.0*S). In both

The same simple model also fits data from individual subjects, as demonstrated by the clear similarities in the best-fitting lines shown in the right panel of Figure 3. Statistically, 16 of the 24 individual regressions were significant at the .05 level, 4 others were marginal ($p < .15$), and the others were insignificant ($p > 0.2$). Over all 24 subjects, the median proportion of variance accounted for was 44%; this increases to 52% when only subjects with reliable individual regressions are considered.

Discussion

Previously we have argued that the ERPs to all words, closed and open class alike, include an N400, so its presence cannot be used as a definitive marker of lexical class. Similarly, we now suggest that the ERPs to all words, closed and open class alike, also include a negativity over left anterior sites whose latency varies with the eliciting word's lexical characteristics, i.e. its length and frequency. Accordingly, we propose that this ERP effect would be more aptly called the Lexical Processing Negativity (LPN), and that its latency be taken as an electrophysiological measure of the effect of lexical factors on word processing. Like the N400, the LPN (aka N280) cannot serve as a qualitative classifier of closed versus open classedness.

One interesting feature of the LPN is that the size of its variation in peak latency (less than 5 msec per log unit of frequency or word length) appears to be much smaller than would be expected for either gaze duration or button-pressing reaction times with the same stimuli. Rather than being a matter for concern, however, this finding can be taken to reveal how and where frequency of a word's daily usage influences word recognition. Reaction time data necessarily reflect the cumulative effects of processing at all stages, whereas ERP latency data can reflect neural activity taking place at particular earlier stages of analysis. Thus, the fact that frequency effects are larger at the final output than at this intermediate stage indicates that frequency impacts processing at multiple points during word recognition and that these effects are cumulative. McRae, Jared, and Seidenberg (1990) provide evidence from word naming in favor of this position, and suggest that such effects could best be explained using models of distributed lexical access processes throughout a broader parallel processing network (such as Seidenberg & McClelland's [1989] word naming model). Other evidence in favor of the accumulation of frequency effects throughout stimulus analysis comes from the ERP study of Polich and Donchin (1988), who noted that differences of ~2 log units of word frequency led to a (mean) 20 msec shift in the peak latency of the P3 in a lexical decision task, but had an appreciably larger (110 msec) effect on the associated lexical decision times.

In any case, establishing the sensitivity of the LPN to word length and frequency, while essential in understanding its functional role during reading, does not, however, reveal what that role is. To date the only hypothesis concerning the functional role of the LPN was based on the assumption that it was a fixed latency N280 elicited only by closed class words and localized over Broca's area (Neville et al. 1992). On this view the N280 is presumed to index "...the activation of processes important in the look up and/or identification of words in a system that only includes representations of closed class words" and perhaps "... processes concerned with parsing sentence structure." (page 251). Our results showing that the N280 is neither specific to closed class words nor fixed in latency suggest a re-consideration of this proposal, although the LPN may, nevertheless, reflect activity linked to a stage of syntactic processing that is sensitive to frequency effects of some kind.[10] Another possibility is that the LPN reflects processing more directly tied to reading, such as the control of gaze or the planning and generation of saccadic eye movements. For the remainder of this report, we outline this alternative hypothesis whose eventual validity should in no way detract from our primary finding of a continuum in LPN latency between open and closed class items.

According to a gaze control hypothesis, the LPN should be sensitive to the same factors that control gaze duration in reading of which length and frequency are two of the more important (Just and Carpenter, 1980). At first glance, the 270-plus millisecond latency of the LPN may seem too long to reflect eye movement-related processes, but it is important to remember that peak latency is a conservative measure of the timing of mental operations and merely serves as an upper limit of the time by which some processing must have occurred. It is also possible that the LPN could be reflecting the activity of an inhibitory process whose timing would naturally place it close to that of eye movements.

cases, however, the concentration on closed class items has reduced our degrees of freedom, and probably seriously affected our p-values (which are $p = .23$ and $p = .15$, respectively). Length alone barely varied between closed class groups in this materials set.

[10]Such effects are not without precedent. Most recently, MacDonald (1994) has demonstrated that differences in frequency underlying verb argument structure preferences influence the resolution of syntactic ambiguity. Thus, in principle, the LPN could be related to the extraction or use of syntactic category information (e. g., its part of speech) subsequent to one or several such processes sensitive to the word's lexical properties.

The role of such inhibitory processes may be highlighted in ERP reading studies due to the requirement that subjects maintain fixation in the center of the screen. This requirement prevents readers not only from making long saccades from word to word, but also from moving their eyes to the “preferred” fixation point within a presented word (i.e., slightly to the left of center; McConkie & Rayner, 1975). Thus, the LPN might reflect some aspect of withholding or controlling eye movements, consistent with a contribution from the frontal eye fields (FEFs) in coordination with nearby anterior language areas. Data from both cortical stimulation (e.g., Luders et al., 1992) and positron emission tomography (PET) localization studies (Fox, et al., 1985) indicate that the brain regions that play a vital role in the generation of volitional eye movements (including the FEFs) in humans are located anterior to the motor strip and dorsal to the classical Broca's area. While direct electrical stimulation of sites in this region can elicit (contralateral) eye movements, stimulation of other nearby areas can also lead to the cessation of ongoing volitional eye movements, or even the *cessation* of both eye movements and speech (Luders et al., 1992). Intriguingly, ERP studies requiring button presses have shown that during trials on which usually appropriate responses had to be inhibited (i.e. “no-go” trials), one observes a negative peak similar the LPN at electrode sites over nearby premotor cortex (Sasaki et al., 1993).[11]

The left laterality of the LPN may reflect either the specific link with language processing or the prevalence of rightward saccades in reading English. One way to adjudicate between these alternative positions would be to investigate the ERPs of subjects reading a language like Hebrew, where saccades are primarily leftward and see if the LPN is altered in its laterality.[12] Another way to explore the laterality of the LPN would be to look at the ERPs to words and sentences in American Sign Language (ASL), given that ASL speakers must suppress saccadic eye movements towards salient, peripheral stimuli moving in either direction.

Accounts that tie the LPN directly to reading processes also provide an alternative explanation of the reported effects on the N280 in individuals for whom reading is a less well-practiced skill. For example, Neville, Coffey, Holcomb and Tallal's (1993) data showed longer latency or less well-articulated LPNs in individuals who were less skilled in reading, whether the comparison was between children and adults, or between children with specific language impairments and those without. Similarly, second language learners such as native ASL speakers who have poorer reading skills in English also were found to show abnormal N280 effects when reading English text (Neville et al. 1992). At the other end of the developmental spectrum, preliminary data in our lab also indicate that the morphology and latency of the LPN change in normal aging, consistent with proposals that older adults suffer declines in inhibitory motor processing (King & Kutas, 1995a).

Whether or not this gaze control hypothesis is eventually confirmed, we believe that the study of the LPN may help us better understand reading and supplement eye movement measures, which now provide most of the compelling data on the nature of online sentence processing. Also, because the LPN can be observed in single word studies (e.g. Nobre & McCarthy, 1994) and appears to be sensitive to length and frequency effects occurring before reaction time, its measure may prove useful in studies of priming and the organization of semantic and lexical memory, in a manner complementary to the more domain-general P300. Last but not least, the fact that LPN can be elicited in paradigms where no overt behavior is required, makes it a more readily accessible measure of a word's processing in members of populations where reaction time data may be difficult to collect or to interpret.

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[11] Note that so far there is no conclusive evidence that the LPN/N280 is actually generated in or near any specific cortical area, and the fact that it is larger over certain anterior sites cannot be taken as firm localization information. Our argument is that the component peak is no less consistent with a generator in the FEF or premotor cortex than in anterior language areas, as suggested by Neville et al. (1992).

[12] While readers of Hebrew show the standard RVF advantage for laterally presented words (e.g., Faust, Kravetz & Babkoff, 1993), they also show a left-of-fixation enlargement of the window of visual attention (Pollatsek, Bolozky, Well, & Rayner, 1981), which is compatible with the scanning hypothesis.

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