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Establishing a time-line of word recognition: evidence from eye movements and event-related potentials

Sara C. Sereno,[CA] Keith Rayner[1] and Michael I. Posner[2]

Psychology Department, 53 Hillhead Street, University of Glasgow, Glasgow G12 8QF, UK; [1]Psychology Department, University of Massachusetts, Amherst, MA 01003, USA; [2]Psychology Department, University of Oregon, Eugene, OR 97403, USA

[CA]Corresponding Author

THE average duration of eye fixations in reading places constraints on the time for lexical processing. Data from event related potential (ERP) studies of word recognition can illuminate stages of processing within a single fixation on a word. In the present study, high and low frequency regular and exception words were used as targets in an eye movement reading experiment and a high-density electrode ERP lexical decision experiment. Effects of lexicality (word *vs* pseudoword *vs* consonant strings), word frequency (high *vs* low frequency) and word regularity (regular *vs* exception spelling-sound correspondence) were examined. Results suggest a very early time-course for these aspects of lexical processing within the context of a single eye fixation *NeuroReport* 9: 2195–2200 © 1998 Rapid Science Ltd.

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Introduction

There is considerable evidence to indicate that eye movements during skilled reading reflect moment-to-moment cognitive processes.[1,2] The average fixation duration of around 250 ms places constraints on the amount of time available for lexical processing. Because eye movements are a motor response, they are programmed well before the end of a fixation. Given this oculomotor latency, lexical access must be well underway within the first 100–150 ms if its complexities are reflected in fixation time. In the present study, we conceptually combined eye movement and event-related potential (ERP) measures to estimate a time-line of processing during eye fixations in reading. Since ERPs reveal a continuous record of brain activity, they can elucidate stages of processing within an eye fixation. The ERP record revealed effects of early lexical processing in the P1, N1 and P2 components. The findings provide a realistic time-line of lexical processing and eye movement programming during reading.

High frequency (HF) and low frequency (LF) regular words (e.g., *week* and *cask*, respectively) were compared with HF and LF exception (non-regular) words (e.g., *hour* and *pint*, respectively) in a reading experiment and an ERP lexical decision experiment. Word regularity refers to the degree to which words follow the spelling-sound correspondence rules in English (cf. *hour* to *your* and *tour*, or *pint* to *hint* and *mint*). While word frequency has been intensively examined in prior eye movement experiments,[3,4] most prior ERP studies have examined word frequency in the context of word repetition with effects in the N400 component.[5,6] On the other hand, word regularity has seldom been investigated in eye movement or ERP studies, but has been studied in naming and lexical decision tasks. The typical finding is that that it takes longer to respond to LF exception than LF regular words, but that HF words show no such effect.[7,8] In the reading experiment reported here, target words were embedded in neutral sentence contexts which subjects read as their eye movements were recorded. Another group of subjects made lexical decision responses to the target words while ERPs were recorded.

Materials and Methods

Subjects: Thirty-two students at the University of Massachusetts participated in the eye movement experiment. They all had normal, uncorrected vision. Forty right-handed students at the University of Oregon participated in the ERP experiment in which reaction time (RT) was measured to target words.

Eye movement data: Eye movements were recorded by an SRI Dual Purkinje Eyetracker, which has a resolution of 10 min of arc. Recording was from the right eye, though viewing was binocular. The output from the eyetracker was sampled every millisecond via a 486 computer. Subjects read sentences presented on a Viewsonic monitor (also interfaced with the computer) and three character spaces equalled 1° of visual angle. A bite bar was used to stabilize head movements. For analysis, the target region was defined as the target itself plus the space in front of it. Data were discarded when subjects failed to directly fixate the target word or when a track loss occurred (a total of 18% of the trials).

ERP reaction time (RT) data: RT was measured to the nearest millisecond via a microswitch connected to a Macintosh II computer. RT data were discarded when there were errors in response, when the RT was greater than 1500 ms or less than 250 ms, and additionally when the RT exceeded a 2 s.d. limit set per subject per condition (a total of 7% of the trials).

ERP voltage data: Scalp voltages were collected using a 64-channel Geodesic Sensor Net[9] at a rate of 250 samples/s. A total of 256 samples (1024 ms) were recorded on the computer for each trial at each electrode, starting 46 samples (184 ms) before stimulus onset. A 60 Hz analogue low-pass filter was applied during recording and a digital 0.1–30 Hz bandpass filter was applied before analysis. The average reference transform (in which each electrode is referenced to the average voltage over the entire scalp surface) was applied to the original right mastoid referenced data before analysis.[10] Trials were rejected when there were movement artifacts (occurring within the first 684 ms of the 1024 ms epoch; i.e. up to 500 ms post-stimulus) in addition to data that had already been rejected from the RT data (a total of 14% of the trials). For analysis, temporal windows of 32 ms (eight consecutive samples) were selected based on the major observable ERP components: the P1 (100–132 ms), the N1 (132–164 ms) and the P2 (164–196 ms). Electrodes were grouped by location[11] and entered as factors into an ANOVA. For each time window, an average voltage amplitude was obtained for each region.

Materials: The target words in the ERP study consisted of 72 HF regular words, 72 HF exception words, 72 LF regular words and 72 LF exception words with frequencies of 238, 263, 8, and 7 per million, respectively.[12] They were all 4, 5, or 6 letters long (word length was equated across the frequency-regularity dimension). Of a total of 192 nonwords, half were consonant strings (e.g., *fhvr*) and half were pronounceable pseudowords (e.g., *welf*). In the eye movement experiment, a subset of 24 words of each of the four types listed above (average word frequency and lengths corresponded to the overall set) were used as targets in 96 sentences.

Experimental design: In the reading experiment, subjects read single-line sentences, each of which contained a target word. They were periodically asked yes–no comprehension questions which they answered without difficulty. In the lexical decision ERP experiment, words and nonwords were presented for 345 ms. Subjects were instructed to press the response button only when the letter string was a word. ERPs were collected for words and nonwords. In both experiments, the materials were presented in a random order.

Results

In the reading experiment, consistent with prior results,[3,4] readers' gaze duration was longer on LF words than HF words (294 *vs* 275 ms; $p < 0.01$). Furthermore, readers looked longer at LF exception words than LF regular words (306 *vs* 281 ms; $p < 0.001$), while there was no such effect of regularity for HF words (278 and 273 ms, respectively). The eye movement data thus demonstrated word frequency and regularity effects similar to those in naming and lexical decision studies, but did so in the context of normal reading and at much shorter processing times.

In the ERP experiment, lexical decision responses were faster to HF words than LF words (490 *vs* 553 ms; $p < 0.001$). Furthermore, responses to LF exception words were longer than LF regular words (558 *vs* 547 ms; $p < 0.01$), and there was, in fact, a marginal effect in the opposite direction for HF words (487 *vs* 494 ms; $p = 0.094$).

The ERP data were analysed for early effects of lexicality, frequency, and regularity. Figure 1 shows interpolated *t*-test plots of the difference between three lexicality conditions: consonant string – word (Fig. 1a), pseudoword – word (Fig. 1b) and consonant string – pseudoword (Fig. 1c). These differences occurred in the P1 (i.e., the first positive ERP component) as early as 100 ms post-stimulus. Figure 2 shows a difference plot for frequency (Fig. 2a). The difference occurred in the N1 as early as 132 ms post-stimulus. Figure 3 shows difference plots for regularity. Since effects of regularity in the ERP components were not evident across subjects, the waveforms of a subset of the subjects who showed the strongest LF regularity effect in the lexical decision data were examined. The difference occurred in the P2

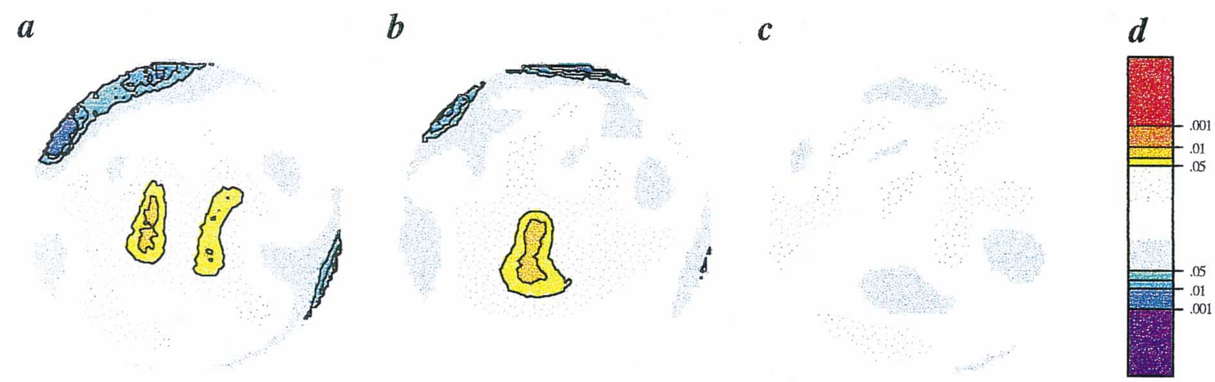

FIG. 1. Scalp topography (front of head is at top). *t*-test plots of the voltage difference interpolations for lexicality in the P1 component at 112 ms post-stimulus: (**a**) consonant strings – words (differences over posterior parietal scalp regions, $p < 0.01$); (**b**) pseudowords – words (differences over posterior parietal scalp regions, $p = 0.06$); (**c**) consonant strings - pseudowords (no differences). Colour bar in (**d**) indicates polarity of difference (red is positive, blue is negative) and degree of significance.

component (Fig. 3a). Figure 3 also shows the corresponding plot for subjects who did not show the behavioral effect (Fig. 3b).

Discussion

While many eye movement studies have examined word frequency effects, only Inhoff and Topolski[7] examined word regularity as a function of word frequency in normal reading. They did not find differential effects of word regularity across frequency class in fixation time measures. In our study, word regularity interacted with word frequency. The discrepancy in results may be due to the fact that we used more experimental stimuli.

Most prior ERP studies have not examined the early components of the waveform for lexical effects, but instead focus on later components. However, a few studies have examined the early components.[13–16] In our study, words differed from both types of nonwords (pseudowords and consonant strings) which did not differ from each other in the P1. Nobre and McCarthy,[13] in the only other study to examine P1 lexicality differences, found opposite results from those reported here. In their study, the two types of nonwords differed from each other but words did not differ from nonwords (the authors themselves remarked that this was quite surprising). In addition, unlike our findings, their effect was localized to two of 50 electrodes (left and right occipital electrodes, O1 and O2). In our study we also found word frequency differences as early as 132 ms post-stimulus in the N1. The only other study to report such differences, Neville *et al.*,[14] did so by using a large 125 ms time window for analysis (from 125 to 250 ms) that cut across many ERP components, including the N1. Again, their effect was localized to two of 12 electrodes (O1 and O2). Finally, differences between LF regular and exception words in our study were evident in the P2 but were restricted to subjects who showed a behavioral effect.

The present contribution maps the eye movement and ERP results onto a single time-line of processing during reading. Figure 4 shows a 300 ms fixation on a word before the eyes move on. This inflated fixation time represents the average fixation time on a word when a valid parafoveal preview is denied (i.e., the word is only read foveally).[17] In this way, viewing conditions in the eye movement and ERP experiments can be made comparable.

The upper part of Fig. 4 shows events which occur as readers move their eyes. At the left end of the time-line, it takes roughly 60 ms for information about the fixated word to travel from the retina to higher cortical areas. Consistent with this, if readers are given 50–60 ms to process text before it is visually masked, reading proceeds quite normally.[18,19] As information about the fixated word contacts higher areas, lexical processing begins. At some point in the processing, the reader shifts attention from the fixated word to the next word in the text and initiates an eye movement motor program.[20,21] At the right end of the time-line, oculomotor latency (the time needed to program an eye movement) limits the interval during which a sufficient degree of lexical processing must be achieved. That is, since fixation duration varies as a function of lexical difficulty, such processing must be well underway in order to trigger the next eye movement. The oculomotor latency is estimated to be around 150 ms.[22] Finally, once a signal is given to move the eyes, about 20 ms elapses before the eye muscles are activated and the saccade begins.

The lower part of Fig. 4 shows corresponding brain activity (revealed in the ERP waveform) and the onset of different types of lexical processing. Lexical processing begins about 100 ms after the word is fixated (arrows indicate the temporal

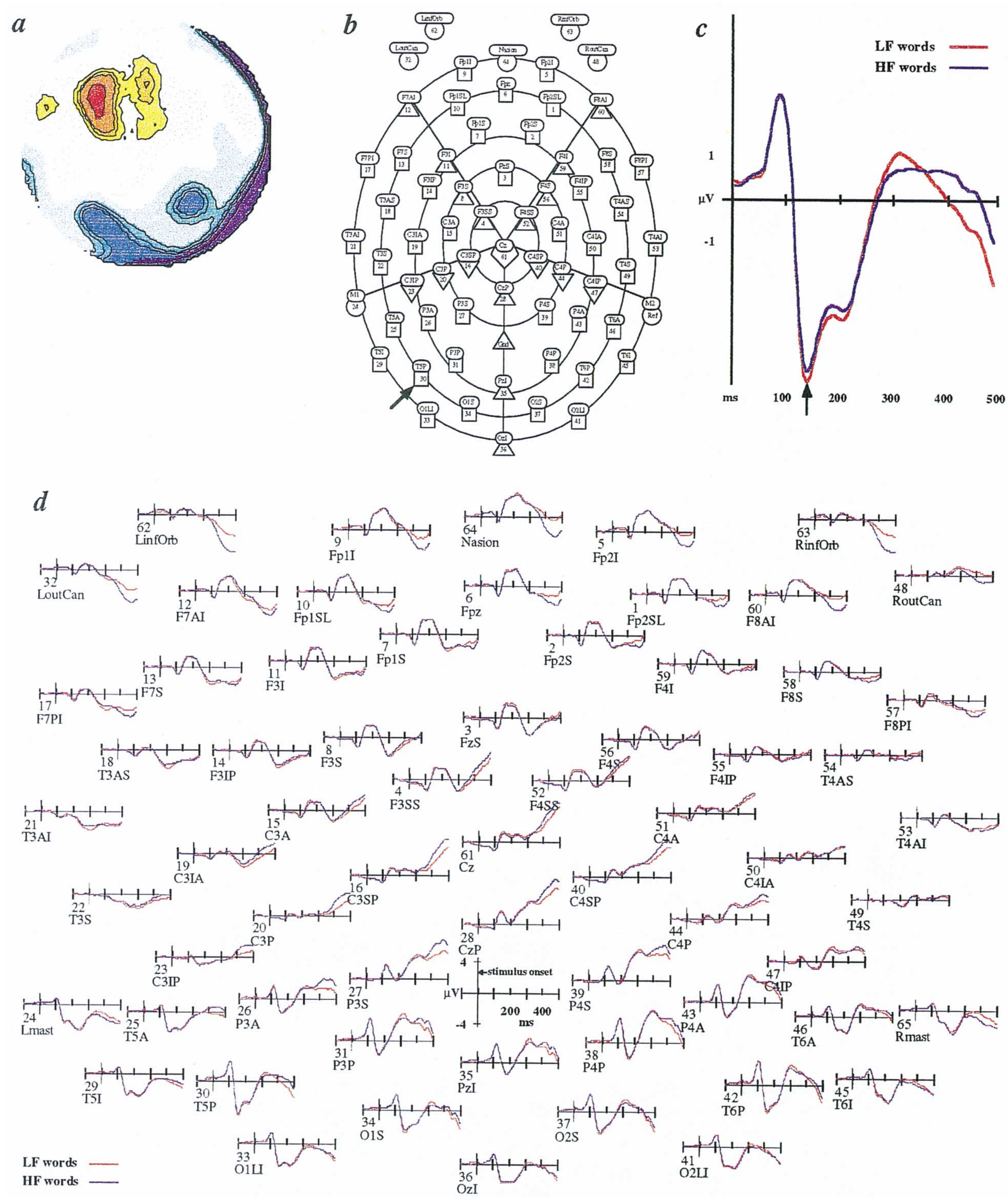

FIG. 2. (**a**) Scalp topography (front of head is at top). *t*-test plot of the voltage difference interpolation for word frequency (LF–HF words) in the N1 component at 144 ms post-stimulus (differences over anterior parietal scalp regions, $p < 0.01$; differences over occipital scalp regions, $p < 0.01$). (**b**) Schematic representation of the 64 electrode locations (front of head is at top of figure). Channel nomenclature is by number as well as a modified 10-20 system. Arrow points to Channel 30; its activity seen in detail in (c). (**c**) Waveform plot of the scalp potentials for LF (red) and HF (blue) words at Channel 30. Arrow indicates N1 difference. (**d**) Grand-averaged ERPs from 40 subjects at each of the 64 electrode sites (front of head is at top). The data were averaged separately for LF (red) and HF (blue) words. Each waveform plot shows a 600 ms epoch, including a 100 ms baseline prior to stimulus onset.

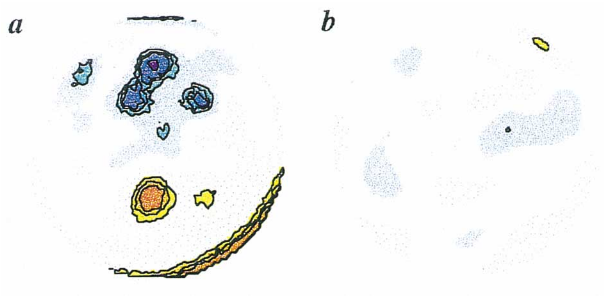

FIG. 3. Scalp topography (front of head is at top). *t*-test plots of the voltage difference interpolations for LF word regularity (LF exception – LF regular words) in the P2 component at 168 ms post-stimulus: (**a**) for 13 subjects showing a behavioral regularity effect, and (**b**) for 13 subjects showing no behavioral regularity effect.

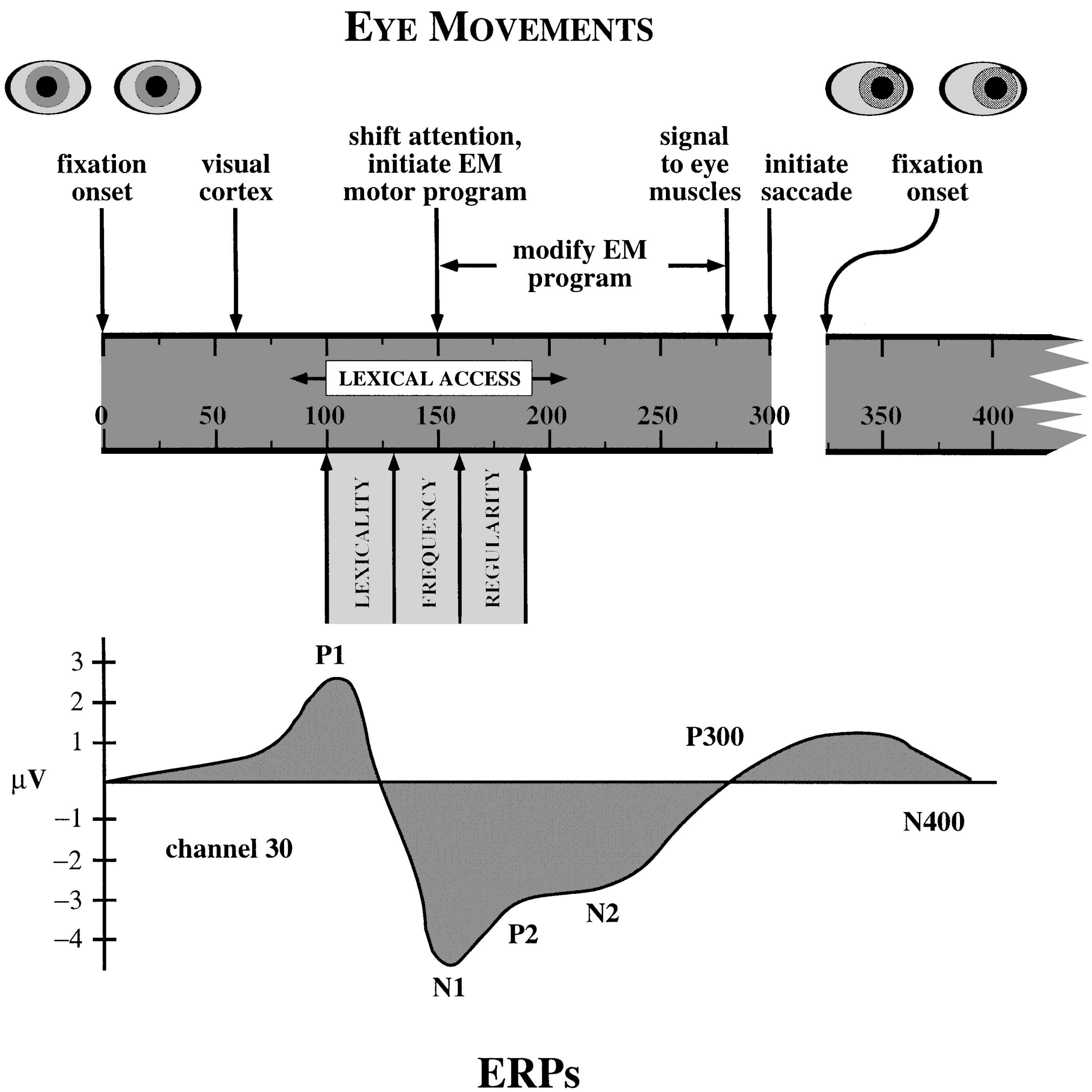

FIG. 4. Time-line of processing a word during reading. The top part represents the events during an eye fixation. The fixation time of 300 ms reflects the somewhat artificial situation in which there is a foveal (without a prior parafoveal) view of the word,[17] a situation present in the ERP experiment. When preview is available during normal reading, the events shown above the time-line can move leftwards. Fixations as short as 200 ms can therefore be influenced by frequency.[4] The designation 'lexical access' does not imply that lexical access is complete (the arrows represent that lexical activity extends over a wide time range). The bottom part depicts the waveform at Channel 30 for LF words stretched over the same time. ERP effects of lexicality, frequency, and regularity are mapped onto the eye movement (EM) time-line.

windows used for analysis of the waveforms), with effects due to frequency and regularity showing up later in processing. One obvious consequence of this analysis is that effects associated with the P300 and N400 (two frequently examined ERP indices) are reflecting post-lexical processes; this is also consistent with the eye movement record in which, by 300 ms, the eyes will have moved onto the next word.

Conclusions

The present study demonstrates that the early components of the ERP waveform can reflect lexical processing. Effects of lexicality, word frequency, and word regularity were evident in the early components of the waveform. These data were then used to estimate a time-line of processing during eye fixations in reading.

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