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Research article

Forehearing words: Pre-activation of word endings at word onset

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ABSTRACT

Occurring at rates up to 6–7 syllables per second, speech perception and understanding involves rapid identification of speech sounds and pre-activation of morphemes and words. Using event-related potentials (ERPs) and functional magnetic resonance imaging (fMRI), we investigated the time-course and neural sources of pre-activation of word endings as participants heard the beginning of unfolding words. ERPs showed a pre-activation negativity (PrAN) for word beginnings (first two segmental phonemes) with few possible completions. PrAN increased gradually as the number of possible completions of word onsets decreased and the lexical frequency of the completions increased. The early brain potential effect for few possible word completions was associated with a blood-oxygen-level-dependent (BOLD) contrast increase in Broca's area (pars opercularis of the left inferior frontal gyrus) and angular gyrus of the left parietal lobe. We suggest early involvement of the left prefrontal cortex in inhibiting irrelevant left parietal activation during lexical selection. The results further our understanding of the importance of Broca's area in rapid online pre-activation of words.

1. Introduction

Behavioral studies have shown that already within 200 ms after hearing the first sounds of a word, e.g. the onset cluster *sp-*, we pre-activate likely completions, like *speeder* and *speaker*, in order to keep up with the rapidly unfolding speech signal [14,15]. Whereas evidence is gathering for the assumption that one word pre-activates the next during sentence processing [2,3,6,11,28,29], the neural correlates of rapid within-word pre-activation are still relatively unexplored. A possible neurophysiological index of pre-activation is the 'pre-activation negativity' (PrAN), a left-lateralized event-related potential (ERP) component thought to indicate enhanced pre-activation of word completions that are likely to appear [24]. PrAN has to date only been observed starting at 136 ms following vowels in stressed syllables, e.g. *ea* in *speaker*. However, behavioral results indicate that pre-activation starts already at word onset [15]. Hence, if PrAN indexes pre-activation, it would be expected to occur even in response to word onset, which in syllables beginning with consonants can be a few hundred milliseconds before vowel onset. It is also presently unclear which stage of pre-activation PrAN indexes: the initial activation of all possible word completions, or rather a subsequent selection among the set of activated completions. Thus, PrAN could reflect incremental selection which is updated as more information becomes available about the word being processed. Identifying the time course and neural sources of a possible PrAN at word onset could give further cues to this. Hence, the aim of the present study was to test for PrAN at word beginnings, trace its possible neural sources, and shed some light on which stages of word-internal pre-activation this ERP component might reflect.

1.1. Pre-activation negativity (PrAN)

The ERP component PrAN was first observed in studies of Swedish word-stem tones that are used to predict suffixes [20]. In Swedish, stems are associated with a low or a high tone depending on the word's suffix. For example, *bil-* 'car' has a low tone when preceding the definite singular suffix *-en* in *bil-en* 'the car,' but a high tone before the plural suffix *-ar* in *bil-ar* 'car-s.' The early negativity was initially thought to reflect an acoustic difference between tones, but in later studies when participants listened to speech melody alone, devoid of lexical content, the effect was not observed [21]. The same negativity has also been obtained for the two tones in different dialects although their acoustic realizations are reversed [19]. Moreover, when the acoustically *least* prominent, low tone was found to increase both a global measure of neurophysiological activity and hemodynamic activation around Wernicke's and Broca's areas [22], it became obvious that the early negative effect did not reflect low-level acoustic properties, but rather some higher-order linguistic function. Using corpus data, it has been seen that an important trait of the low tone is that it is associated with on average

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11 times fewer word completions than the high tone [24]. Since there are fewer possible continuations available for the low tone, it is a better predictor for word completion. Accordingly, the negativity was found to correlate with response time facilitation for suffixes cued by low tones [25]. The high tone on the other hand is associated with both suffixes as well as a potentially infinite number of compounds.

Apart from their function as cues to upcoming suffixes, the tones do not in themselves convey any meaning. Therefore, increased activation in language-associated Wernicke's and Broca's areas observed for the highly predictive low tone has been interpreted as an indication that the early negativity actually indexes *pre-activation* of upcoming word endings. This has the test implication that the pre-activation negativity (PrAN) should increase gradually with a decrease in possible completions a word stem has, and thus the more certain listeners can be about the ending of a word. The test implication was confirmed in a study on PrAN at stem tone onset in the stressed vowel [24]. Other evidence suggesting that PrAN indexes pre-activation of word endings is on the one hand that subjects showed high accuracy in predicting and retrieving suffixes masked by coughs, based on the preceding tone alone, and on the other hand that accuracy in suffix retrieval correlated with PrAN amplitude [25]. To establish PrAN as a more general index of pre-activation, however, it is necessary to ascertain that the effect can be found independently of tone. In the present study, we therefore removed all influence of tone, averaging all ERPs over the two tones and summing the number of possible continuations for the tones. Further, the time-locking point at word onset occurred $M = 129$ ms before vowel onset, $SD = 71$ ms, where stem tone information would start gaining more importance had its effects not been averaged out.

1.2. Stages of pre-activation

Although it seems plausible that PrAN reflects pre-activation, it is not known which stage of pre-activation is indexed. Behavioral results have shown that pre-activation of words is a complex process. Thus, the 'Cohort model' developed by Marslen-Wilson and colleagues [14,15], distinguishes between three main stages of word processing. During the initial "lexical access" stage, the first speech sounds activate all possible candidates for word completion, i.e. *speaker*, *speeder*, *spot* etc. for *sp-* irrespective of their contextual fit [15,32]. Magnetoencephalographic studies comparing real words to pseudowords suggest that the initial access stage might start with left frontotemporal activation as early as 30–50 ms following word onset [12,23]. BA 45 and 47 in left ventral inferior frontal gyrus (IFG), as well as the right BA 47 homologue are thought to be involved in this initial activation, since they respond to *increased* number of possible completions [7,30,31].

At around 200 ms following word onset, the "lexical selection" stage sets in [15]. During selection, candidates for word completion are ruled out based on the incoming speech stream. Thus, if the listener hears *spea-*, s/he can inhibit *spot* as an impossible alternative. For each speech sound, the listener can inhibit more alternatives, until a point is reached where there is only one possible candidate. This is the "word recognition point" [14]. The first evidence for this selection stage was obtained by subtracting simple reaction time from the time it takes to repeat an auditorily perceived word. It was shown that subjects can make a lexical selection at about 200 ms from word onset [15].

Whereas the left ventral IFG has been related to lexical activation, the dorsal part of the left IFG, including BA 44 (pars opercularis, IFGpo) and 45 (pars triangularis), seems to be involved in lexical selection. Thus, degree of selection in pseudowords has been studied in a brain-imaging study by varying the number of possible completions word-initially (after the first two speech sounds) just before the pseudoword recognition point, i.e. where there were no longer any possible completions [31]. Words that had a relatively high number of completions initially as compared to the final number of completions involved rapid inhibition of a larger number of irrelevant alternatives. This increase in selection demands augmented activity in BA 44 and 45. Left BA 44 has also shown to be sensitive to selection demands in verb generation [26,27]. Activity in BA 44 has further been seen to be accompanied by posterior activation in inferior parietal cortex, BA 40, in the presence of lexical competitors, when participants were instructed to use their gaze to choose an image corresponding to a spoken word [17]. A possibility is thus that lexical selection might involve prefrontal inhibition of phonological representations in inferior parietal cortex, in line with the frontal lobe's general involvement in inhibition of potentially interfering memory representations [18]. To summarize, activations in the IFG are especially informative regarding the stage of word pre-activation PrAN reflects. Thus, activity in the ventral part indicates an early stage of activation of possible word forms, whereas dorsal activity suggests selection by inhibition of irrelevant forms.

1.3. Assessing PrAN at word onset

The main objective of the present study was to further investigate the PrAN effect previously found at vowel onset by examining data for evidence for pre-activation already at word onset. An additional objective was to identify neural sources for within-word pre-activation. Therefore, we tested neurophysiological and blood-oxygen-level-dependent (BOLD) response for 30 different words spoken in sentences using ERP and functional magnetic resonance imaging (fMRI) on the same participants. Word onsets ranged from having a low to a high number of possible completions after perception of the first two speech sounds. We chose to measure completions for the first two speech sounds mainly because there is often co-articulation in onsets which could make it possible already at the first speech sound to identify the following sound. To detect a possible PrAN, words were divided into two groups based on their having few ($M = 219$, *Range* = 46–355) or many ($M = 1083$, *Range* = 595–2003) possible completions after perception of the first two phonemes. ERPs from a pre-activation negativity were tested in an ANOVA with *possible completions (few, many)* and *lexical frequency of the completions (low, high)* as factors. Although lexical frequency was not found to affect the previously investigated vowel-onset PrAN [24], this measure could be more important at the earlier word onset point, where selection demands are stronger. If the candidates are frequent words, this could increase the certainty about the word completion. To obtain a more exact appreciation of the influence of these two factors, a linear regression model further tested whether a decreased number of *possible word completions* and an increased *lexical frequency* of the completions gradually augmented PrAN amplitude. We then performed a global root mean squares (gRMS) analysis [10] to see in which time-window PrAN had the greatest global activity. This analysis also aimed to confirm the generality of regression functions found at single electrodes. To assess the neural source of word onset PrAN, we first related peak global ERP activity to the BOLD signal for each word compared to silence. We then measured the overlap between this BOLD signal and that of a *few − many possible word completions* contrast in a conjunction analysis (individual analyses in supplementary material). This was done in order to find the increased BOLD activity for few possible continuations corresponding to the maximal PrAN activity.

2. Materials and methods

2.1. Participants

Eighteen right-handed young adults (8 females, mean age 25.3 years, $SD = 5.3$) participated in the experiment. The study was approved by the local ethics review board in Lund, part of the Swedish Central Ethical Review Board (www.epn.se, approval number 2012/37).

2.2. Stimuli and procedure

ERP and fMRI data from [22] were investigated to find evidence for

word-initial PrAN. In light of the present research questions, a new division of data as well as new time-locking points were applied to the material. Crucially, whereas the data analysis in [22] was concerned with tone and suffix processing, the present study averaged stimuli in a balanced fashion over both tones and suffixes, yielding datasets which were unrelated to those in [22]. Participants listened to 30 different Swedish nouns inserted into carrier sentences of the kind *NAME got NOUN for lunch/Christmas* (supplementary material). ERP and fMRI data were collected from the same participants in two sessions separated by a few days, using the same experimental paradigm for comparability. ERPs and fMRI were time-locked to NOUN onset in the test stimuli in an event-related design. Response times were time-locked to suffix onset. Brain data was related to the number of possible word completions at the first two phonemes of the target words as well as the lexical frequency of the completions. These measures were calculated on the basis of a pronunciation-based lexicon database [24] constructed from the NST database [1] and the PAROLE corpus (https://spraakbanken.gu.se/swe/resurs/parole). Both measures were log transformed for further use in evaluation of brain data. Stems and suffixes were spliced to avoid predictability of word ending, and were presented once with each stem-suffix combination in each task. This gave a total of 60 sentences per condition, and 240 sentences in the whole experiment. The critical noun occurred at 925 ms into the carrier sentences, $SD = 92$ ms. Word stems were on average 426 ms long, $SD = 64$ ms, and suffixes 241 ms, $SD = 24$ ms.

Two different tasks in two different blocks kept participants alert, and controlled for task effects. One task was to press a left or right button using index fingers to judge number (singular/plural) in the target noun. Hand-number association was balanced within participants. The other task was to alternately press the same left and right buttons to indicate where the sentences ended. Both tasks were irrelevant for pre-activation of word endings, since the initial speech sounds did not give any cues to either grammatical number or sentence length. Accordingly, no significant difference was found in number judgment response times between word beginnings having few, $M = 654$ ms, $SD = 171$ ms, and many, $M = 666$ ms, $SD = 167$ms, possible word completions, $F(1, 17) = 1.35$, $p = 0.262$. Nor was there any difference in accuracy for word beginnings with few, $M = 98.9\%$, $SD = 1.6\%$, and many, $M = 98.9\%$, $SD = 1.2\%$, possible completions, $F(1, 17) < 0.01$, $p = 0.997$.

2.3. Brain potentials

A Synamps^2 amplifier (Compumedics Neuroscan, USA) and a 32-channel Easycap (Falk Minow, Germany) recorded electroencephalography using 23 Ag/AgCl sintered ring electrodes mounted according to the international 10/20 system. Impedances were kept below 5 kΩ. FCz served as reference during recording, and CPz was ground. Reference was recalculated to average mastoids offline. Sampling frequency was 250 Hz. An online band-pass filter (cut-off frequencies 0.05 Hz and 70 Hz) and an offline low-pass filter (30 Hz) were applied.

Sixty epochs of 600 ms following critical word onset were extracted per condition and participant. A 200 ms time-window preceding the time-locking point was used for baseline correction. Epochs with ERPs exceeding ± 100 μV following ocular artefact compensation using independent component analysis (runica algorithm) [8] were discarded. There was no significant difference in rejection rate between few, $M = 5.1\%$, $SD = 8.6\%$, and many word completions, $M = 4.0\%$, $SD = 6.5\%$, $F(1, 17) = 2.9$, $p = 0.105$. The spared epochs were also resorted by item for regression analysis. PrAN was measured as the first negative deflection from the point of divergence between few and many completions until the end of its peak, resulting in a time-window between 136 and 204 ms with a maximum amplitude at electrode C3. Average ERPs per subject and condition in this time-window were submitted to a repeated-measures ANOVA with factors *possible word completions* (*few*, *many*), *lexical frequency* (*low*, *high*), and *task* (*suffix*, *sentence end*). To detect the peak global activity for few possible completions, reference-free, global root mean squares (gRMS) were calculated [10]. A rise to a gRMS peak for few possible completions could be identified at 184–204 ms, which was also evaluated in a repeated-measures ANOVA. Average ERPs and gRMS values per item in the same time-windows were submitted to regression analyses with continuous independent variables *possible word completions* and *lexical frequency* to see whether there was a gradual relation between these variables and ERP and gRMS peak amplitude.

2.4. Functional magnetic resonance imaging

FMRI data from the same participants was acquired using a Siemens Magnetom Skyra 3.0T scanner and a 32-channel head coil. Analyses were performed with SPM12 software (Wellcome Department of Cognitive Neurology, http://www.fil.ion.ucl.ac.uk/spm) [22]. In the first-level analysis, beta values were estimated for few and many possible completions and for overall stimulus exposure in fixed-effects analyses using event-related design. Average gRMS per item and subject in the peak time-window was used as a parametric modulator in the word–silence contrast, providing beta values related to gRMS peak. In the second-level analysis, beta values entered a full factorial ANOVA with 3 dependent levels: low, high, and gRMS peak. To see the overlapping activity between the few − many contrast and the gRMS peak-related activity, a conjunction analysis between the few–many contrast and the gRMS parametric modulator was then made (supplementary material). A threshold of $p < 0.005$ (uncorrected) and an extent threshold of 20 voxels were used. An inclusive mask involving language-related areas (bilateral inferior and middle frontal gyri, superior, middle, and inferior temporal gyri, insula, as well as angular and supramarginal gyri of the parietal lobe) defined by the Talairach Daemon database [9] in the Pick Atlas software toolbox was used [13]. Final results were overlaid on the adult MNI ICBM 152 symmetrical T1 contrast standard brain [4].

3. Results

The ERPs showed a pre-activation negativity (PrAN) for few possible continuations as compared to many. It was observed as a negative deflection at 136–204 ms following word onset, reaching its maximum at the left central electrode C3, $F(1, 17) = 6.62$, $p = 0.020$, $\eta_p^2 = 0.280$ (Fig. 1). The effect did not interact with task, $F(1, 17) = 1.52$, $p = 0.235$, or lexical frequency, $F(1, 17) = 0.10$, $p = 0.756$. Global root mean squares (gRMS) were calculated to see at what time point the maximum overall neural activity was found [10], producing a rise to an activity peak for few possible continuations at 184–204 ms, $F(1, 17) = 9.71$, $p = 0.006$, $\eta_p^2 = 0.364$ (Fig. 1).

A regression function was found for C3 in the 136–204 ms time-window, $F(2, 29) = 7.13$, $p = 0.004$, $r = 0.588$, $r^2 = 0.346$, $SEE = 0.677$ (Eq. (1)), where PrAN increased as the number of possible completions of word beginnings decreased, $p = 0.002$, and the lexical frequency of those possible completions increased, $p = 0.009$.

$$PrAN = 3.0(\log\ possible\ completions) - 2.0(\log\ frequency\ of\ completions) - 1.4 \quad (1)$$

Removing one independent variable at a time still produced a significant regression function for number of possible continuations, $F(1, 29) = 4.57$, $p = 0.049$, $r = 0.363$, $r^2 = 0.132$, $SEE = 0.766$, but not for possible word frequency, $F(1, 29) = 1.02$, $p = 0.320$. The gRMS peak at 184–204 ms also produced a regression function showing the same relationship between the independent variables, $F(2, 29) = 4.40$, $p = 0.022$, $r = 0.496$, $r^2 = 0.246$, $SEE = 0.905$ (Eq. (2)). Thus, the gRMS peak increased for word beginnings with fewer possible completions, $p = 0.007$, and greater lexical frequency of those completions, $p = 0.018$.

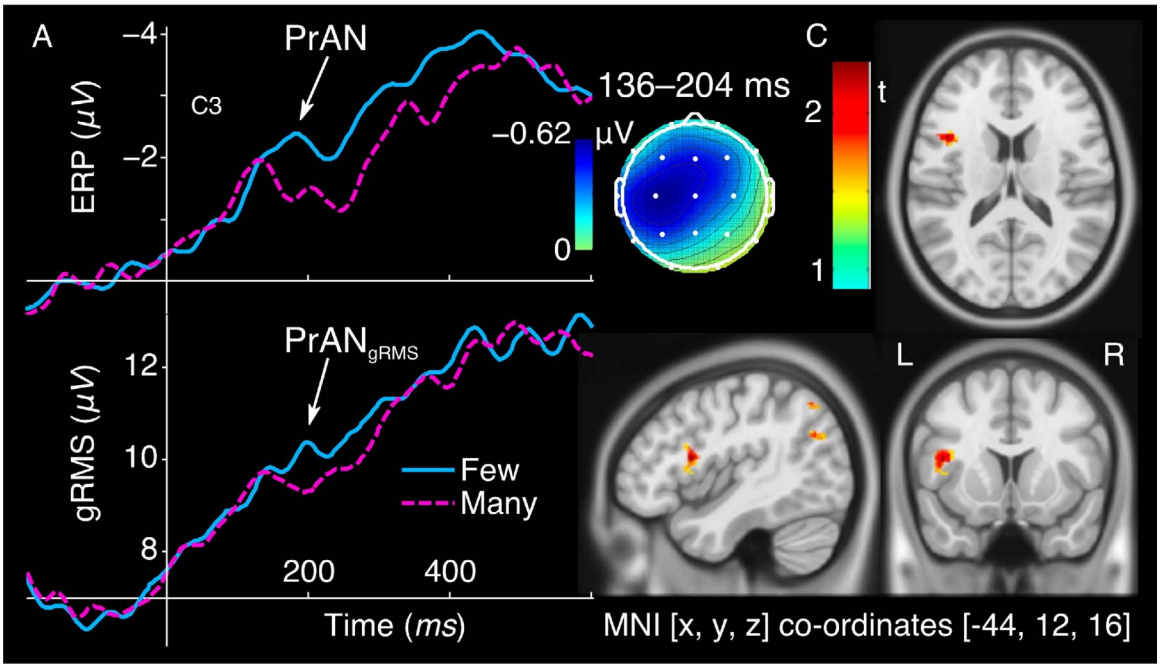

Fig. 1. Pre-activation negativity (PrAN) measured at word onset and correlated neural sources. Event-related potentials (ERPs), subtraction topography at 136–204 ms (A), and global root mean squares (gRMS) (B) for few vs. many possible word completions. BOLD effect in Broca's area (pars opercularis of left inferior frontal gyrus) and the angular gyrus of the left parietal lobe for conjunction between the few–many contrast and gRMS peak activity ($p < 0.005$, cluster extent threshold 20 voxels) (C).

$$PrAN_{gRMS} = -2.8(\log\ possible\ completions) + 2.6(\log\ frequency\ of\ completions) + 4.9 \quad (2)$$

Few possible continuations conjoined with gRMS peak-related activity yielded increased BOLD effect in the pars opercularis of the left IFG (IFGpo, −44, 12, 16; 118 voxels), in the angular gyrus of the left parietal lobe (−48, −66, 32; 47 voxels and −38, −64, 50; 47 voxels), and in the left middle frontal gyrus (−34, 30, 26; 36 voxels). No activations were found in the right hemisphere.

4. Discussion

Results show that word onsets with few possible completions are associated with a pre-activation negativity (PrAN) in the ERPs between 136 and 204 ms, with peak global activity between 184 and 204 ms. The peak global activity was related to BOLD activation mainly in Broca's area, specifically the pars opercularis of the left IFG (IFGpo, BA 44). Left-hemisphere sources are in accordance with what would be suggested by the left-lateralization of the ERP effect. The onset of PrAN observed at 136 ms following word onset seems to be too late to reflect the lexical access stage of the Cohort model. Timewise, PrAN would rather seem to correspond to the subsequent lexical selection stage, thought to start around 200 ms following word onset [14,15]. The neural sources would also suggest that selection is involved. Thus, the increased activity found in prefrontal cortex suggests that what is captured in the PrAN is selection of likely word representations through inhibition of irrelevant representations. Activation in the left IFGpo has been related to this kind of lexical selection in the presence of different competing possible words [17,31]. The activity in the angular gyrus of the left parietal lobe seems to corroborate this hypothesis, since the IFGpo projects to the posterior cortex through this area [5]. The inferior parietal cortex more generally is thought to be involved in lexical competition [17]. Therefore, a possibility is that inferior parietal activation of phonology-meaning associations is regulated by the IFGpo through inhibition of irrelevant alternatives. The relation to ERP activity would suggest that this occurs at the lexical selection stage during the first 200 ms following word onset, in line with previous behavioral findings [15].

Additional support for the hypothesis that PrAN reflects selection comes from previous work which has found PrAN at 136 ms following *vowel* onset [24], which would be at 265 ms from word onset in the present study. This effect is probably seen in the negative deflection following that indicated as PrAN in the ERPs presented in Fig. 1. However, the effect is less prominent in the present study, since a division between many and few possible completions would need to be made at that point based not only on the first two phonemes as in the present study, but also based on other eventual onset consonants, vowel, as well as stem tone, as was done in [24]. We suggest therefore that PrAN might involve a sequence of negative-going deflections responding to increasing selection of the relevant word completion as more information becomes available from the unfolding word.

Word-onset PrAN showed both similarities and differences as compared to the previously described vowel-onset PrAN. In a similar way, both effects increase gradually with decreasing number of possible word completions. A difference is that at word onset, PrAN also increased with increasing lexical frequency of the possible completions. This was also true for peak global ERP activity. In other words, here we found rapid neural activation for word beginnings that had few possible completions which would form frequent words. However, the lexical frequency effect had not been observed for a slightly later point in processing. Hence, as the uniqueness point approaches in word processing and fewer possible completions remain, lexical frequency seems to become less important for lexical selection. Finally, it is difficult to state an exact onset point of PrAN. Here, onset was measured as the point where ERPs for word beginnings with few and many possible completions started differing at 136 ms. However, a negative slope is seen for both conditions even before that, which might reflect processes of pre-activation common both to word beginnings with few or with many possible completions.

In sum, results from the present study provide further support for the idea that PrAN reflects predictive certainty: the fewer possible outcomes there are and the more frequent those outcomes are, the stronger the brain can commit to pre-activation of those outcomes. We showed that this process could be measured starting as early as 136 ms following word onset. The analysis was based on information from the

first two speech segments, excluding cues from word accent tones. Thus the results should be more readily transferrable to non-tonal languages like English than previous findings. The pre-activation is thought to consist of activation of phonological representations in posterior cortex and selection among these, modulated by Broca's area (IFGpo), starting shortly after word onset. The results can also possibly contribute to a deeper understanding of findings of impaired lexical pre-activation in Broca's aphasia [16].

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neulet.2017.08.030.

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