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Research article

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

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A R T I C L E I N F O

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A B S T R A C T

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