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Tone-grammar association within words: Concurrent ERP and fMRI show rapid neural pre-activation and involvement of left inferior frontal gyrus in pseudoword processing

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ABSTRACT

Using a concurrent ERP/fMRI paradigm, we investigated how listeners take advantage of morphologically relevant tonal information at the beginning of words to predict and pre-activate likely word endings. More predictive, low tone word stems gave rise to a 'pre-activation negativity' (PrAN) in the ERPs, a brain potential which has previously been found to increase along with the degree of predictive certainty as regards how a word is going to end. It is suggested that more predictive, low tone stems lead to rapid access to word endings with processing subserved by the left primary auditory cortex as well as the supramarginal gyrus, while high tone stems – which are less predictive – decrease predictive certainty, leading to increased competition between activated word endings, which needs to be resolved by the left inferior frontal gyrus.

1. Introduction

In spoken language processing, listeners take advantage of information at the beginning of words to pre-activate likely word endings (Breen, Dilley, McAuley, & Sanders, 2014; Cutler & Otake, 1999; Marslen-Wilson, 1987; Roll et al., 2015; Söderström, Horne, Frid, & Roll, 2016). In Swedish, a language with tones, tonal information can be used to access lexical and grammatical information. The tones in Swedish are associated with word stems, and are used to predict and access possible continuations following the word stem. It has been suggested that this morphophonologically driven predictive mechanism is reflected in the 'pre-activation negativity' (PrAN), a fronto-temporal event-related potential (ERP) which begins at around 100 ms after onset of a predictive cue (such as a word stem with a tone). PrAN amplitude correlates inversely with the number of possible word ending types a word stem cues (Söderström et al., 2016). Thus, it is suggested that the probabilistic pre-activation of likely endings is facilitated when fewer possible continuations enter into competition when the word stem is being processed. It has previously been found that lexical access in morphologically complex words is modulated by the probability of encountering a suffix given a particular stem (Solomyak & Marantz, 2010). Furthermore, the morphological structure of words has been observed to influence auditory word recognition and aid rapid prediction of phonemes (Ettinger, Linzen, & Marantz, 2014). Thus, the processor can be claimed to take advantage of statistical regularities inherent in the association between stem tones and suffixes in Swedish, so that more predictive word stems can be assumed to create stronger expectations about and pre-activate upcoming word endings. Less predictive stems are expected to give rise to an increase in competition between different endings. However, it is still not clear whether the mechanisms indexed by PrAN are only sensitive to lexical properties of word stems, or also to the morphophonological tone-suffix association modulating the predictability of upcoming word continuations. In the present study, we attempted to isolate the abstract connection between stem tones and suffixes, aiming to determine whether PrAN would still be elicited in the absence of lexical information on the stem, and to investigate the neural underpinnings of this effect. To achieve this, we used semantically empty pseudoword stems with different tonal patterns, connected to existing singular or plural suffixes, to see whether and how different stem tones function to pre-activate possible endings when the only linguistic cue the processor has to work with is the morphophonological connection between word stem tones and possible endings. In addition to using pseudoword stems, some test words had endings masked by light coughs, allowing us to see whether participants, using only the stem tone, could predict the meaning of a suffix even when it has been replaced by a cough. In order to investigate the

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mechanisms reflected in the pre-activation negativity, we took advantage of the excellent temporal resolution of ERPs as well as the spatial resolution of functional magnetic resonance imaging (fMRI) in a concurrent experimental paradigm.

In Swedish, each word stem (such as *båt*, 'boat') is associated with either a low tone (known as 'accent 1') or a high tone ('accent 2'). The tone associated with the stem is dependent on the word's ending. For example, if the singular suffix *-en* is connected to the word stem *båt*, forming the inflected word $båt_L$*-en*, 'boat' SG DEF, the stem is pronounced with a low (L) tone, while the plural suffix *-ar* induces a high tone (H) onto the stem ($båt_H$*-ar*, 'boat' PL INDEF). Furthermore, all productive compounds have a high tone on the initial morpheme. As such, the high tone is a cue signalling that at least one more syllable will follow, such as the head of a compound of any length ($båt_H$*-hus*, 'boat house', $båt_H$*-hus-brand*, 'boat house fire', etc.). This also holds if the word stem or constituent is a loan word, such as *chatt* ('chat room'), giving rise to compound words such as $chatt_H$*-diskussion* ('chat room discussion'). Consequently, since monosyllabic stems with no ending are automatically associated with the low accent 1 tone, this tone always cues a smaller number of possible word forms while the high accent 2 tone cues more possible continuations (such as compounds). Using a lexicon database, Söderström et al. (2016) found that high stem tones cue almost 11 times as many possible continuations, the majority being compounds. Another way of putting this is in terms of *entropy*, defined as a function of the distribution of probabilities of all upcoming items (Willems, Frank, Nijhof, Hagoort, & van den Bosch, 2016). Thus, high stem tones give rise to high entropy – being associated with a larger number of possible upcoming word endings – while low stem tones are associated with lower entropy, leading to greater certainty about upcoming word endings. In Ettinger et al. (2014), it was proposed that low entropy at the onset of morphologically complex words increases neural activity in e.g. transverse temporal gyrus in primary auditory cortex, while high entropy – in the case of less predictive word stems – prompts the parser to delay predictive processes until entropy has been reduced.

All previous ERP studies on Swedish word tones have found greater negativities for low stem tones as compared to high stem tones. Testing the hypothesis that the predictive relationship between stem tone and possible endings should be reflected linearly in PrAN amplitude, Söderström et al. (2016) found that word stems which cue fewer possible continuations indeed elicit greater pre-activation negativities, providing strong support for the idea that the effect is sensitive to the number of possible continuations of a word stem, and that it possibly indexes some type of probabilistic pre-activation of likely word endings. In support of this account, it has been found that unexpected word endings lead to N400 (Kutas & Hillyard, 1980) and P600 (Osterhout & Holcomb, 1992) effects (Gosselke Berthelsen, Horne, Brännström, Shtyrov, & Roll, 2017; Roll, 2015; Roll, Horne, & Lindgren, 2010; Roll, Söderström, & Horne, 2013; Roll et al., 2015; Söderström, Horne, & Roll, 2017), both of which have recently been suggested to reflect decision certainty and revision processes associated with disconfirmed predictions (Droge, Fleischer, Schlesewsky, & Bornkessel-Schlesewsky, 2016; Hinaut & Dominey, 2013; Rabovsky & McRae, 2014).

In a previous ERP/fMRI study using existing words as test stimuli (Roll et al., 2015), PrAN appeared to be composed of an earlier component with temporo-parietal topography and a later part with a more frontal distribution. PrAN amplitude in the early time window correlated most strongly with blood-oxygen-level dependent (BOLD) activity in the left anterior transverse temporal area, Brodmann area (BA) 41, as well as in the superior temporal gyrus, BA22, indicating a strong connection between tones and word forms, and possibly reflecting increased neural activity to lower entropy, as proposed in Ettinger et al. (2014). In the case of existing words, it is possible that frequent combinations of stem and suffix are stored and accessed as whole-word items. However, it is not obvious how the pre-activation of word continuations occurs when there are no stored whole-word representations that can be accessed from long-term memory, i.e. when new words or pseudowords are processed. The present study aimed to isolate the pre-activation mechanism driven by the purely formal morphophonological association between stem tones and endings. In the absence of stored whole-word representations, the hypothesis was that the proposed pre-activation of word endings would be more dependent on the morphophonological structure of the words. Specifically, items with greater predictive potential as regards possible continuations (low tone stems) could be assumed to have stronger associations in memory to word endings such as suffixes. We thus hypothesised that more predictive stem tones (in this case, low (accent 1) tones) would be processed via a more direct association with suffix representations in the temporal lobes, including primary auditory cortical areas (e.g. BA41 (Ettinger et al., 2014; Jacquemot, Pallier, LeBihan, Dehaene, & Dupoux, 2003)) as well areas in the inferior parietal lobe such as the supramarginal gyrus suggested to be involved in e.g. the activation of likely upcoming word endings (Roll, Söderström, Frid, Mannfolk, & Horne, in press). On the other hand, less predictive stem tones (i.e. high (accent 2) tones) could lead to increased processing in prefrontal areas. Specifically, activation of frontal areas for high stem tones would be expected since these stems lead to greater lexical competition that needs to be suppressed and resolved before the ending can be accessed and the word can be fully processed (Blumstein, 2009; Righi, Blumstein, Mertus, & Worden, 2010; Söderström et al., 2016; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999; Thompson-Schill et al., 1998).

2. Materials and methods

2.1. Stimuli

The stimuli used in the present study were recorded by a male Central Swedish speaker in an anechoic chamber. The stimuli were pseudoword stems with either a low or high tone followed by either singular or plural suffixes, or a light cough (e.g. $kvup_L$*-en*, 'kvup' SG DEF, $kvup_H$*-ar*, 'kvup' PL INDEF or *kvup-COUGH*). These words were embedded in carrier sentences such as *Rut fick kvupen/kvupar till* ***lunch*** ('Rut got the kvup/kvups for **lunch**'). Sentence focus was on the final word so that the test stimuli could be produced with non-focal word accents. Participants were asked to judge as quickly as possible whether the person in the sentence got one (singular) or many (plural) thing(s). Since low tones are associated with singular endings and high tones with plural endings, the correct response for the cough condition was "singular" for low tones followed by a cough, and "plural" for high tones, i.e., assuming that the stem tone pre-activates its suffix, we expect that even in the case of a cough ending, the correct response would be made on the basis of the tone. Response time and response accuracy data were measured from the onset of the suffix or the cough. All sentences in all conditions were identical up to the onset of the critical word as well as after offset of the suffix, meaning that the stem tone (aligned with the beginning of the stem vowel) was the first point at which participants could begin to pre-activate the suffix. There were 40 stems in a 40 × 6 condition design, for a total of 240 stimuli. In two conditions (LoValid and HiValid), the stem was associated with its appropriate suffix. In another two conditions (LoInvalid and HiInvalid), an invalid tone-suffix combination was created using cross-splicing, yielding incorrect combinations such as $*kvup_L$*-ar* with a low stem tone and plural suffix (LoInvalid) and $*kvup_H$*-en* with a high stem tone and a singular suffix (HiInvalid). In the other two conditions, the suffix was replaced with a light cough, which was identical for both conditions (LoCough ($kvup_L$*-COUGH*) and HiCough ($kvup_H$*-COUGH*)). A cough was used (as in e.g. Warren (1970)) instead of silence in order to make the stimuli slightly more natural, as well as to better approximate the acoustic properties of the suffixes (i.e. as compared to silence). For all stimuli, including the cough conditions, the task was to judge as quickly