

Word tones cueing morphosyntactic structure: Neuroanatomical substrates and activation time-course assessed by EEG and fMRI



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ABSTRACT

Previous studies distinguish between right hemisphere-dominant processing of prosodic/tonal information and left-hemispheric modulation of grammatical information as well as lexical tones. Swedish word accents offer a prime testing ground to better understand this division. Although similar to lexical tones, word accents are determined by words' morphosyntactic structure, which enables listeners to use the tone at the beginning of a word to predict its grammatical ending. We recorded electrophysiological and hemodynamic brain responses to words where stem tones matched or mismatched inflectional suffixes. Tones produced brain potential effects after 136 ms, correlating with subject variability in average BOLD in left primary auditory cortex, superior temporal gyrus, and inferior frontal gyrus. Invalidly cued suffixes activated the left inferior parietal lobe, arguably reflecting increased processing cost of their meaning. Thus, interaction of word accent tones with grammatical morphology yielded a rapid neural response correlating in subject variability with activations in predominantly left-hemispheric brain areas.

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1. Introduction

Understanding everyday speech requires identification of speech sounds, word stems and affixes, as well as integrating this information in grammatical structures – all at rates of up to 6–7 syllables/second (Levett, 1989). This remarkable performance would not be possible without the help of cues in speech that continuously provide information about the upcoming structure of words and clauses (Cutler, Dahan, & Donselaar, 1997; Roll, Horne, & Lindgren, 2011). Many languages use intonation to cue grammatical structure at the clause level. This type of interaction is known to give rise to inter-hemispheric signal exchange due to the left hemisphere's specialization in modulating grammar and the right hemisphere's dominance in regulating intonation (Friederici & Alter, 2004; Sammler, Kotz, Eckstein, Ott, & Friederici, 2010). However, while grammar processing is believed

to rely on left-lateralized perisylvian regions (Marslen-Wilson & Tyler, 2007), laterality of tonal processing is less clear-cut; not all kinds of tonal information are considered to have a mainly right-hemispheric substrate. Crucially, word tones in Chinese or Thai, which serve categorical lexico-semantic distinctions, have been found to increase activation in areas of the left superior temporal gyrus (Xu et al., 2006). If both word tones and grammar show a left hemisphere bias, word tones cueing grammatical affixes should give rise to tone-grammar association activations concentrated in the left hemisphere. This can be tested in Swedish, where listeners use word tones on stems to unconsciously predict which suffix words will have (Roll, Horne, & Lindgren, 2010). Brain areas responsible for morphological prediction have to be rapidly activated, since in disyllabic words, prediction occurs from one syllable to the next, which limits the time frame for this process to ~150 ms at fast speech rates (Roll, Söderström, & Horne, 2013). To address the spatio-temporal dynamics of these fundamental processes connecting prosody to grammar, the present study investigated the neural substrates that enable rapid associations between stem tone and suffix using a combination of temporally

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and spatially resolved neuroimaging methods. Electroencephalographic (EEG) recordings established a timeline of brain responses to stem tones and suffixes, and functional magnetic resonance imaging (fMRI) was used to identify the location of the brain areas involved in the processing.

1.1. Morphosyntactic word tones

Swedish (and related Norwegian) have long been known to have word tones similar to those in e.g. Chinese, called “word accents” (Bruce, 1977; Chao, 1976). However, in Swedish and Norwegian, the tone that is realized on a word’s stem depends on which suffix is attached to the stem (Riad, 2012; Rischel, 1963). Therefore, the Swedish stem *hatt* in *hatt + en* (‘the hat’) has a low tone, known as “Accent 1” (Fig. 1, A1), whereas the same stem in *hatt + ar* (‘hats’) has a high tone, or “Accent 2” (Fig. 1, A2), due to the suffix difference.

Word accent tones have a clear function in facilitating rapid word-processing in Swedish (Roll et al., 2010). Thus, native speakers use the association between stem tone and suffix to predict which ending a word will have already when hearing the stem. This has been seen in increased response times for judging the meaning of suffixes that were invalidly cued by the wrong stem tone (Söderström, Roll, & Horne, 2012). Electrophysiological studies have shown a difference in the processing of Accent 1 and Accent 2 starting around 140 ms from tone onset (Roll et al., 2010, 2013). This differential effect has previously been thought to reflect an increase in neural activity for Accent 2 (expressed as a positivity on the scalp surface) due to the high tone’s relative auditory salience compared to the low Accent 1 tone (Roll et al., 2010). However, the electrophysiological effect has only been seen to appear if the tonal contrast is realized within existing words (Roll et al., 2013), suggesting that it might reflect a process involved in the predictive function of word accents (signaling upcoming suffixes) rather than indexing tonal salience. In human vocalizations that do not include meaningful lexical or syntactic information (humming), the auditory salience of the high Accent 2 tone has instead produced an increase in the auditory N1 component (Roll et al., 2013).

Accent 1 is more useful than Accent 2 for predicting its related suffixes, since it is associated with a well-defined set of endings, whereas Accent 2, in addition to connecting to a set of suffixes, occurs in compound words as well, e.g. *hattband* ‘hat band.’ Accordingly, validly cued Accent 1 suffixes have yielded shorter response times than Accent 2 suffixes (Roll et al., 2013;

Söderström et al., 2012). Therefore, it seems likely that the differential effect previously found for word accents should be interpreted as a negativity for Accent 1 indexing greater preactivation of memory traces of the suffixes associated with the tone.

1.2. Neural substrates for processing tone and grammar

Whereas the above studies have given some limited information on the EEG time-course for tone-suffix interaction, the neural substrates underlying this interaction remain unknown. However, based on studies in Thai, Chinese, and non-tonal languages like English or German, morphosyntactic tone could be expected to engage a number of brain areas. One strong candidate is the left inferior frontal gyrus (LIFG), which is assumed to subserve grammar processing (Marslen-Wilson & Tyler, 2007). Processing of word structure (morphology) has been seen to specifically involve the ventral part of LIFG, Brodmann area (BA) 47 (Koester & Schiller, 2011; Tyler, Marslen-Wilson, & Stamatakis, 2005). Dichotic listening studies indicate that native speakers of tone languages such as Mandarin and Norwegian engage the left hemisphere more than nonnative speakers when discriminating word tones (Moen, 1993; Wang, Jongman, & Sereno, 2001; Wang, Sereno, Jongman, & Hirsch, 2003). Studies involving brain-damaged patients have confirmed the dominance of the left hemisphere in word tone processing in these languages (Hughes, Chan, & Su, 1983; Moen & Sundet, 1996; Naeser & Chan, 1980; Packard, 1986) as well as in Thai (Gandour et al., 1992), Toisanese Chinese (Eng, Obler, Harris, & Abramson, 1996), Cantonese (Yiu & Fok, 1995), and Shona, a Bantu language in which tone is conditioned by word structure in a manner similar to Swedish and Norwegian (Kadyamusuma, De Bleser, & Mayer, 2011).

Brain imaging studies have found activation in the left frontal lobe and inferior parietal lobe for tasks involving active discrimination between lexical word tones (Gandour et al., 2000, 2003, 2004; Klein, Zatorre, Milner, & Zhao, 2001). A problem when interpreting results of tone discrimination in languages with lexical tone is that there is a confound between tonal and lexical analysis. In order to isolate the prelexical processing of tones, Xu et al. (2006) let Thai speakers listen to Thai tones, Mandarin tones, and Thai tones superimposed on Chinese syllables. They found overlapping activation for tone processing in both known words and unknown words in the temporal plane of the left superior temporal gyrus (STG), involving BA 22, 41, and 42. This area is convergent with that associated with the analysis of segmental speech sounds (consonants and vowels) (Graves, Grabowski, Mehta, & Gupta, 2008). In other words, it would seem that familiar word tones are processed like any other phonologically distinctive sound in the STG even without any associated meaning. The activity in frontal and parietal cortex in previous studies might have been due to selection related to the tone-discrimination task and processing the word meaning. Still, no neuroimaging evidence is available for the predictive morphosyntactic processes of the kind that characterize tone-suffix associations such as those in Swedish.

1.3. Present study

We used fMRI and EEG to comprehensively investigate morphosyntactic tone processing in the brain. EEG has excellent temporal resolution, and fMRI is superior in detecting sources of brain activity. Although electrophysiological and metabolic measures are sensitive to different temporal and spatial scales, using both methods in the same paradigm on the same participants allowed us to conjecture possible relationships between temporally and spatially resolved effects. We hypothesized that the brain treats the difference between word accent tones in Swedish as a phonological distinction. Therefore, we expected the increased

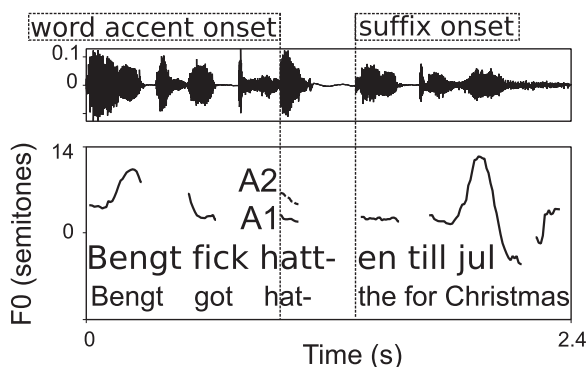


Fig. 1. Example of a stimulus sentence. Acoustic waveform and fundamental frequency (F0) are shown. The solid F0 line at *hatt* ‘hat’ represents the low Accent 1 tone associated with the definite singular ending-*en*. The broken line indicates what the corresponding high Accent 2 tone would have been had the ending been plural-*ar*.

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