Phonemic and subphonemic cues in prediction: Evidence from ERP, eye-tracking and Danish words with and without stødbasis

Anna Hjortdal & Mikael Roll
Centre for languages and literature, Lund University

Abstract

The brain is constantly trying to predict the future and phonological and prosodic cues are used to anticipate forthcoming information. Even cues on the subphonemic level such as vowel transitions, nasalisation and assimilation across word boundaries are useful in anticipating upcoming speech. In event-related potential (ERP) studies examining subphonemic and lexical/phonological mismatches, only the latter yielded N400 effects, an ERP component associated with lexical prediction error. The results indicate that phonetic cues are resolved prelexically. However, subphonemic cues still seem to be used in prediction as evidenced by valid cues yielding faster fixations in eye-tracking studies and invalid cues modulating P600 amplitudes, indicating structural violations and context updating.

Introduction

In recent years, the idea that prediction plays a vital role in language processing has won terrain (DeLong et al., 2005; Kutas et al., 2011). Within this framework, linguistic items are pre-activated before being perceived. The predictions are based on 'subjective Bayesian probability' which is the believed probability of certain events based on previous experiences (Bar, 2007; Friston, 2005). Predictions are carried from cognitively higher to lower levels. If predicted features fail to manifest themselves, prediction errors are carried back to higher levels (Rao & Ballard, 1999).

Several studies have found that lexical, phonological and prosodic structures such as whole words (DeLong et al., 2005; León-Cabrera et al., 2017), word-initial phonemes (Roll et al., 2017; Söderström et al., 2016), word tones (Roll, 2015; Roll et al., 2017; Roll et al., 2015; Söderström et al., 2016; Söderström et al., 2017b; Söderström et al., 2017a) and syntactically-related tones (Söderström et al., 2018) can function as cues to the input string. Evidence for this comes, among other things, from event-related potential (ERP) studies showing that unexpected structures yield ERP components associated with prediction error such as the N400 and P600. Further, more predictively useful cues produce an electrically more negative pre-activation negativity (PrAN) deflection, a component modulated by the predictive strength of phonological cues (Roll et al., 2017; Söderström et al., 2016). Even cues on the subphonemic level appear to be used in prediction. Response time, eye-tracking, event-related potential (ERP) and magnetoencephalographic (MEG) studies have shown that listeners are sensitive to fine-grained acoustic differences on the subphonemic level (Archibald & Joanisse, 2011; Flagg et al., 2006; Grosvald & Corinna, 2009; Martin & Bunnell, 1981, 1982; McQueen et al., 1999; Mitterer & Blomert, 2003; Streeter & Nigro, 1979; Warren & Marslen-Wilson, 1987) and such cues appear to be used actively to predict upcoming structures (Beddor et al., 2013; Dahan et al., 2001b; Salverda et al., 2014). In the following, we wil review the literature on how subphonemic (phonetic, coarticulatory) cues affect spoken word recognition and prediction and discuss subphonemic versus phonological cues. Further, we will discuss potential implications for how the prosodic features Swedish word accents and Danish stød are to be understood.

Phonetic cues

Listeners are sensitive to subtle phonetic cues. 'Subcategorical phonetic mismatches', as they were termed by Whalen (1984), are phonetic cues spliced into a new environment in which they conflict with existing cues but are not enough to change phonemic identity. In a lexical decision task with English speakers, Streeter and Nigro (1979) found that response times were faster when VC formant transitions were valid than invalid, even when there was no difference in the intelligibility of words. Whalen (1991) obtained similar results for lexical decisions but observed that effects of subcategorical mismatches were reduced in auditory naming tasks.

Marslen-Wilson and Warren (1994) and McQueen et al. (1999) examined the influence of the lexical status of invalid cues for speakers of English and Dutch respectively. In both experiments, CVC words were cross-spliced so that some stimulus words had valid coarticulatory cues, some had formant transitions from a lexical competitor word (e.g. English *jog* with formant transitions from *job*) while others had formant transitions from a non-word (e.g. *jog* with formant transitions from *jod*). Words with valid cues were identified faster than those with invalid cues, but there was no difference in response latencies between the two different invalid conditions. However, in an eye-tracking study, Dahan et al. (2001b) found that participants were the slowest at fixating on a target picture when transitions came from a competitor word, somewhat faster when they came from a non-word while the fastest response times were found for words with valid transitions. This was interpreted as evidence for lexical competition, the activation of a word also depending on activation of competing candidates. Thus, activation of the target word would be inhibited by activation of a competitor, or, from a predictive processing point of view, activation of a competitor by mismatched phonetic cues yielded misguided predictions, thus slowing down fixations.

Similar results have been obtained for other types of coarticulation. In studies with speakers of English, mismatched presence or absence of nasalisation during a vowel preceding an oral or nasal consonant yielded longer response times (Fowler & Brown, 2000) and, for oral consonants invalidly cued by a nasal vowel, a delay in neuromagnetic activity in a magnetoencephalographic (MEG) study (Flagg et al., 2006). Nasal consonants following oral vowels were also delayed, but not significantly, probably reflecting that in English, nasalised vowels are stronger predictors of an upcoming nasal consonant than are oral vowels of oral consonants because a nasal following an oral vowel is still viable. In an eye-tracking study, also with speakers of English, Beddor et al. (2013) found that listeners fixated on images with nasal consonants (e.g. *send* rather than *said*) faster when nasalisation started already during the vowel. When eye movement programming delay was taken into account, listeners started fixating on target words before the onset of a nasal consonant, indicating that listeners take advantage of coarticulatory cues to predict what is further down the input string.

Listeners are also sensitive to coarticulation across syllable (Martin & Bunnell, 1981, 1982) and word boundaries (Gow, 2003). Martin and Bunnell (1981, 1982) found that vowel-vowel subcategorical phonetic mismatches across syllables yielded longer response times. They speculated that information already heard was used to predict outlines of the signal yet to come. In a combined behavioural and mismatch negativity (MMN) ERP study, Grosvald and Corinna (2009) observed that listeners were sensitive to vowel-to-vowel coarticulation across three intervening segments. Some listeners were sensitive to coarticulation across as much as five segments. Salverda et al. (2014) showed that coarticulation during English definite articles allowed listeners to fixate more rapidly on a target word, suggesting that short and phonetically reduced function words such as *a* and *the* play an important role in facilitating processing of following content words in English.

Listeners appear to continuously make use of what cues are available. In an eye-tracking study, McMurray et al. (2008) found that early (voice onset time (VOT) and formant transition slope) and late (vowel length) cues to voicing and manner contrasts in English modulated the probability of eye movements to pictures of target and competitor words as these cues became available. Even children are sensitive to phonetic cues (Cross & Joanisse, 2018; Paquette-Smith et al., 2016; Zamuner et al., 2016). In an eye-tracking study, Paquette-Smith et al. (2016) found that English-speaking 2-year-old children are sensitive to subphonemic mismatches, but word recognition was less disrupted than for phonemic mismatches. The findings indicate that listeners use coarticulatory cues to constantly make and update predictions. The next question is whether segments invalidly cued by subphonemic cues, such as subcategorical phonetic mismatches, produce the same neural error signals that have been observed for phonological cues.

Subphonemic mismatches and prediction error

In a combined response time and ERP study with speakers of English, Archibald and Joanisse (2011) examined lexical, phonemic and coarticulatory mismatches. Participants looked at colour stock photographs on a screen and listened to stimuli. They were asked to answer whether the picture and word matched by pressing buttons on a keypad. Stimulus words came in five conditions: 1) coarticulatory and lexical match (e.g. picture of a hat, heard *h^{a}at*), 2) coarticulatory and lexical mismatch (e.g. picture of a hat, heard *h^{o}ot*), 3) coarticulatory match and lexical mismatch (e.g. picture of a hat, heard *h^{a}ot*), 4) lexical match and coarticulatory mismatch (e.g. picture of a hat, heard *h^{o}at*) and 5) unrelated (e.g. picture of ship, heard *h^{a}at*). They found that only lexical mismatches yielded N400 effects, an ERP effect associated with lexical prediction error (DeLong et al., 2005) while both conditions yielded an increased negativity between 230 and 310 ms after word onset, interpreted as a phonological mismatch negativity (PMN). The PMN is modulated by pre-lexical phonological processing, although its status as a separate component is debated due to inconsistencies in reported topography, timing and sensitivity (Lewendon et al., 2020). No differences in response times were reported, except for the unrelated condition. Archibald and Joanisse (2011) interpreted the findings as evidence that subphonemic information does not influence word-level selection but is processed at the prelexical level.

Hjortdal and Roll (submitted) examined how phonetic, coarticulatory cues and contrastive, phonological cues interact in a combined response time and ERP study. Effects from the two phases of the Danish creaky voice feature, stød, were isolated in a cross-splicing design. The first phase displays phonetic differences in e.g. pitch while the second phase, realised as creaky voice, is the phonological locus of stød (Basbøll, 2014). Stød can distinguish word meanings but is also associated with specific morphological structures (Basbøll, 2005). For instance, monosyllabic nouns which have stødbasis and thus support stød have stød in definite singular, but lose stød when pluralised with *-e*. The presence or absence of stød during a stem can therefore cue upcoming information. Words were cross-spliced, occurring in eight different conditions in singular and plural and cued by 1) valid phonetic and stød/non-stød cues, 2) valid phonetic but invalid stød/non-stød cues, 3) invalid phonetic but valid stød/non-stød cues and 4) invalid phonetic and stød/non-stød cues. Words lacking stødbasis, which do not support stød due to sonority constraints, were included as controls. Such words do not attain stød when they engage in morphological constructions which, in words with stødbasis, would lead to stød/non-stød alternations. However, words without stødbasis still display small and consistent phonetic differences. Invalid phonological stød/non-stød cues yielded lower response accuracy and increased response times, in line with previous findings (Clausen & Kristensen, 2015). Phonetic cues in the control condition did not affect neither accuracy nor response times while phonetic cues in the stød condition only affected response times in the absence of a valid phonological cue. Invalid phonological cues yielded N400 and P600 effects while invalid phonetic cues led to no such effects in the stød condition. In the control condition, singular suffixes invalidly cued by plural stems yielded a P600 effect.

Pre-activation negativity

While the ERP components N400 and P600 have been associated with prediction error, the pre-activation negativity (PrAN) has been interpreted as an index of the actual pre-activation of linguistic information (word endings or syntactic structure) and is modulated by the predictive strength of phonological cues (Roll, 2015; Roll et al., 2015; Söderström et al., 2016). PrAN amplitudes are higher for word beginnings (i.e. the first 2-3 phonemes of a word) with highly frequent continuations and few lexical competitors. Also, Swedish accent 1, which is associated with much fewer continuations than accent 2, produces more negative PrAN amplitudes, indicating that PrAN reflects the degree to which continuations can be predicted (Roll et al., 2017; Söderström et al., 2016). PrAN has been identified for prosodic cues such as word initial fragments, word tones and syntactically-related tones (Roll, 2015; Roll et al., 2017; Roll et al., 2015; Söderström et al., 2016; Söderström et al., 2017b; Söderström et al., 2017a).

Studies using fMRI have shown increased activity for pre-activation (PrAN) in the primary auditory cortex and surrounding areas between

70 and 150 ms after stimulus onset (Roll et al., 2015; Söderström et al., 2018), which is thought to reflect stronger activation of more predictively useful forms. Later, after 200 ms, PrAN correlates with activity in Broca's area. This activation has been interpreted as reflecting selection through inhibition of irrelevant candidates (Roll et al., 2017; Roll et al., 2015; Söderström et al., 2017b). In the Hjortdal and Roll (submitted) study with Danish stød, plural first phases yielded early PrAN effects while stød yielded late PrAN amplitudes, the latter reflecting that stød occurs under more constrained conditions than non-stød and thus is a better predictor.

Discussion

In both ERP studies examining phonological/lexical and subphonemic cues (Archibald & Joanisse, 2011; Hjortdal & Roll, submitted), N400 modulations were reported for lexical/phonological mismatches while subphonemic mismatches yielded no such effects. This could be interpreted as support for the proposal that subphonemic cues are processed prelexically without constraining lexical processing (Archibald & Joanisse, 2011). While the N400 is modulated by differences on the lexical level, the P600 has been reported for violations in form and structure (Osterhout & Holcomb, 1992; Rodriguez-Fornells et al., 2001; Roll et al., 2010; Sassenhagen et al., 2014). The component can be understood as context updating in terms of morphological and syntactic structure (Sassenhagen et al., 2014). N400 effects have been reported for stimulus words differing from a target image by just one phoneme. For instance, Desroches et al. (2009) and Archibald and Joanisse (2011) reported N400 modulations when participants looked at e.g. an image of a cone while hearing *comb* or looking at an image of a hat while hearing *hot.* Further, an N400 effect was reported when the Danish creaky voice feature stød/non-stød did not match definite singular/indefinite plural suffixes.

It might be that N400 effects occur when a word strongly inhibited or perhaps even ruled out from lexical competition, e.g. due to a speech error or for experimental reasons, is eventually recognised. Such a re-entrance might show up in the ERP signal as an N400 effect, a signal of lexical prediction error (DeLong et al., 2005). Subphonemic phonetic mismatches, on the other hand, might not lead to words dropping out completely from lexical competition. However, phonetic cues still appear to be used in prediction, as evidenced by eye-tracking studies showing that valid phonetic cues yield faster fixations on target words (Beddor et al., 2013; Dahan et al., 2001b; Salverda et al., 2014) and the P600 component reported in Hjortdal and Roll (submitted), indicating prediction error and the PrAN, indicating that phonetic cues were used for prediction.

If this interpretation is correct, it has implications for how the roles of Swedish word accents and Danish stød should be interpreted. Swedish words have either a high or a low tone on the stem. Like Danish stød, the tones (word accents) can distinguish meanings but can also be induced by suffixes and thus cue word endings (Riad, 2014; Rischel, 1963; Roll et al., 2010). P600 effects have been reported for Swedish word accents invalidly cuing suffixes (Gosselke Berthelsen et al., 2018; Roll, 2015; Roll et al., 2010; Roll et al., 2013; Roll et al., 2015) while N400 effects have only rarely been reported (Gosselke Berthelsen et al., 2018). It might be that only Danish stød, and not Swedish word accents, takes itself into what is traditionally known as the lexically contrastive level. As mentioned above, stød as well as word accents can distinguish word meanings as well as function as a cue to upcoming information. However, the phonetically reduced structure of Danish might give stød an even more prominent role. In spontaneous speech, a final schwa is assimilated to the preceding vowel or consonant, often resulting in almost identical singular and plural forms, e.g. *land* [lanˀ] 'country' and *lande* [lann̩] 'countries' (Grønnum, 2005). However, if the singular has stød, the forms are kept apart (Basbøll et al., 2011). The N400 modulation reported for stød/non-stød-suffix mismatches could therefore indicate that stød is becoming lexicalized for monosyllabic singular nouns in Danish – and more so than Swedish word accents. Further support for this interpretation comes from the finding that for at least one participant in the stød study, the presence or absence of stød, rather than suffixes, appeared to be the principal factor in determining whether a test word was singular or plural (Hjortdal, 2021).

To sum up, listeners do seem to use subphonemic cues to predict upcoming information. Such cues appear to be handled prelexically without constraining lexical processing, as proposed by Archibald and Joanisse (2011). Further, Swedish word accents would also appear to be dealt with prelexically, only rarely making their way to the lexical level, while an N400 effect suggests that Danish stød does make its way to the lexical level.

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