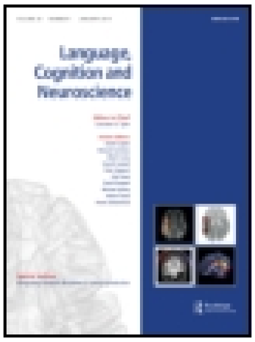

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Putting underspecification in context: ERP evidence for sparse representations in morphophonological alternations

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ABSTRACT
Numerous studies have shown evidence for a sparse lexicon in speech perception, often in the guise of underspecification, where certain information is omitted in the specification of phonological forms. While previous work has made a good case for underspecifying certain features of single speech sounds, the role of phonological context in underspecification has been overlooked. Contextually-mediated underspecification is particularly relevant to conceptualizations of the lexicon, as it is couched in item-specific (as opposed to phoneme-specific) patterning. In this study, we present behavioural and ERP evidence that surrounding phonological context may trigger underspecified lexical forms, using regular morphophonological alternations in English.

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Underspecification; prefix processing; LAN; phonological alternation; phonological context

1. Introduction

The specific pronunciation of any word varies widely between speakers, situations, and linguistic contexts, and numerous models of speech perception have sought to address the so-called "invariance problem", including those which employ underspecification. Underspecification is a theoretical concept which suggests that representations are sparse, with certain types of information systematically omitted. These sparse forms are utilized to make speech perception more robust to variation, as matching input forms to stored representations of phonemes or words hinges only on the remaining specified elements. In the neurolinguistic literature, there is evidence which both supports (cf. Eulitz & Lahiri, 2004; Friedrich, Eulitz, & Lahiri, 2006) and refutes (Tavabi, Elling, Dobel, Pantev, & Zwitserlood, 2009) the existence of underspecified forms. By and large, these studies have focussed on coronal underspecification, using the Featurally Underspecified Lexicon theory (Lahiri & Reetz, 2010), a variant of Radical Underspecification (Kiparsky, 1982).

However, underspecification in linguistics has a long history in the theoretical literature, and several fundamentally different accounts underspecification have been proposed, including Archiphonemic Underspecification (Inkelas, 1995; Trubetzkoy, 1969) and Contrastive Underspecification (Archangeli, 1988; Halle, 1959) in addition to Radical Underspecification (Kiparsky, 1982). While these theories disagree in the degree to which the lexicon is underspecified, they align in a single principle: that underspecification is justified in cases where a sound alternates in a fully predictable pattern.

This leaves a surprising gap in the experimental literature, where prior research has been focussed on not only the most extreme version of underspecification, but has also failed to examine those areas where the linguistic case for underspecification is strongest: where the phonological context of the word itself causes regular, predictable alternations. In order to examine the effect of context on underspecification in the lexicon, we designed an ERP experiment which used complex morphological forms in English, composed of "in-" and "un-" prefixed words. These prefixes are an informative pairing, as both contain coronal nasals ([n]), but participate in different phonological processes. The "in-" prefix assimilates the place of the nasal as part of a productive phonological process ("i[m]perfect" vs. "i[n]tolerant"), while "un-" does not (compare "u[n]problematic" and "u[n]tidy").

1.1. Underspecification in ERPs

A large literature looking at neural markers of underspecification has focussed on coronality as a determining factor for underspecification. This view is particularly championed by Lahiri and colleagues under the auspices of the Featurally Underspecified Lexicon (FUL) theory (Lahiri & Reetz, 2002), but has grounding in earlier

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approaches in theoretical linguistics under the masthead of Radical Underspecification (Kiparsky, 1982). The special treatment of coronals is because this place of articulation is designated the "default"/"unmarked" place of articulation, and all unmarked feature values are taken to be underspecified in this theory. Thus for places of articulation, coronals are always underspecified, and any other place of articulation requires specification.

A large number of studies using the FUL paradigm have shown processing asymmetries involving coronal and labial segments in nonwords. Lahiri and Reetz (2002) posit that auditory features are extracted from the speech stream and converted to phonological features which are then matched to the lexicon. The importance of underspecification is found in their system of matching, which is ternary, allowing for three situations: matching, mismatching, and not-mismatching (in the case of a feature extracted from the input signal but not specified underlyingly). When surface labials are mapped onto underlyingly coronal (thus underspecified) segments, no disruptions in processing are observed, as this is a not-mismatching case. However, a mismatch occurs when surface coronals are mapped onto underlying labial segments (which must be specified). In this situation, studies have shown either a mismatch negativity (MMN; Cornell, Lahiri, & Eulitz, 2011; Eulitz & Lahiri, 2004; Scharinger, Lahiri, & Eulitz, 2010) or an N400 (Friedrich et al., 2006; Friedrich, Lahiri, & Eulitz, 2008) depending on the type of stimuli used.

More recent research in underspecification has sought to expand on this work by looking at additional areas in which phonological content may be underspecified. This has included coronal underspecification in fricatives (Schluter, Politzer-Ahles, & Almeida, 2016), voicing underspecification (Hestvik & Durvasula, 2016; Hwang, Monahan, & Idsardi, 2010), manner underspecification for nasals (Cornell, Lahiri, & Eulitz, 2013), height underspecification in vowels (Scharinger, Monahan, & Idsardi, 2012), and tone underspecification in Mandarin (Politzer-Ahles, Schluter, Wu, & Almeida, 2016). These studies provide support for underspecification in a number of theoretically-motivated domains outside of the traditional coronal paradigm. However, there are also a handful of counterexamples which have been published. In particular, studies have shown that underspecification analyses do not hold up when contextual information is also available. In these cases, context is argued to play a larger role in the perception of speech sounds (Mitterer & Blomert, 2003; Tavabi et al., 2009).

Contextual information and underspecification are not necessarily mutually exclusive, though they have been treated that way in most experimental paradigms. In fact, the origin of underspecification in linguistic theory lies in the idea of contextual information itself triggering underspecification in the lexicon. In many linguistic theories of underspecification (Archangeli, 1988; Halle, 1959; Kiparsky, 1982), surrounding phonological context actually triggers underspecification in a given segment. For instance, in English, words which begin with "st" may only be followed by a vowel or "r". In a word like *straight*, the only information that is required of the medial "r" is that it is a consonant; the phonotactic constraints on English allow for no other possibilities. In this case, the phonological context determines that the medial "r" can be almost completely underspecified, but in other contexts, "r" would be much more richly specified. The reasons for underspecifying in this case differ fundamentally from those used in more radical accounts. Here, underspecification serves only to reduce any redundant knowledge a speaker would be required to store about a specific sequence of sounds, favouring instead online mechanisms which can be invoked to "fill in" the missing specifications if necessary.

However, word-internal context is not the only type of context which may be relevant to the predictability and therefore specification of a sound. Surrounding context also plays a determining role in morphophonological alternations, for instance, in determining which version of the English plural to use: an "-s" (in "backs"), a "-z" (in "bags"), or an "-ez" (in "batches"). In these cases, the voicing of the plural is always determined by the word to which it is attached. Many in linguistic theory have argued that morphemes which alternate predictably in this manner are also underspecified (Inkelas, 1995; Trubetzkoy, 1969), as there is no particularly strong argument to specify the morpheme in question as either "-s" or "-z". Note that this differs fundamentally from more radical approaches to underspecification, including FUL, which focus on system-wide underspecification of specific features. With contextually-driven accounts, underspecification is tied instead to specific lexical items. Here, it is the plural morpheme itself that is underspecified because of its alternation, rather than a feature common to all "s" or "z" sounds. In the literature, Archiphonemic Underspecification accounts focus exclusively on this type of predictable alternation, and therefore take the most conservative approach to lexical underspecification. In these theories, it is only these predictably alternating items which are underspecified, and all other sounds receive a full specification in the lexicon.

Within cognitive neuroscience, this type of lexically-bound underspecification has not been investigated to the same depth as the more radical varieties of underspecification used in the FUL theory. In fact, it is noteworthy that a vast majority the preceding studies have used MMN paradigms with either single segments or nonword syllables, which do not allow for an exploration of lexical effects on underspecification. These lexically-bound contextual effects on underspecification form the backbone of linguistic theories of underspecification, and are common to all conceptualizations of underspecified lexicons, and are yet unexplored in the neurolinguistic literature. The present study seeks to fill this gap by looking at underspecification in morphophonological alternations.

1.2. Morphophonological alternation in English

Alternations in English can be found in a number of structural domains, including in prefixes (e.g. "e[m]-power"/"e[n]-act"), within stems (e.g. "sw[i]m"/"sw[a]m") and in suffixes (e.g. the plural [-s]/[-z]/[-ez]). The present study makes use of alternations in the "in-" and "un-" prefixes, which participate in different phonological processes suggesting different degrees of underspecification.

The "in-" prefix participates in a particularly complicated process of assimilation. Before vowels and coronal stems, the [n] form is used (e.g. "i[n]articulate", "i[n]tolerant"). In other cases, such as before [l] and [r], the final segment completely assimilates (e.g. "i[l]logical", "i[r]replaceable"), losing the nasal articulation entirely. Preceding [gn] clusters ("i[]gnorant", "i[]gnoble") the final segment deletes, leaving only the "i". Finally, the nasal is retained but assimilates in place to following labial consonants ("i[m]probable", "i[m]material") and velars ("i[ŋ]conclusive"), although some report the velar assimilation is not produced consistently across speakers (Bauer, 1983, p. 219). In short, the final consonant of the "in-" prefix varies widely in specific realisation, but is consistently derivable by the following context (i.e. the stem consonant to which it is attached).

Because this pattern of assimilation is quite complicated, and restricted to this specific prefix (as opposed to being a general pattern of found throughout the English lexicon) some linguists, particularly those working in morphology, have questioned whether this assimilation process is productively available. The question of productivity is not trivial, as it impacts whether the "in-" prefix is stored with an underspecified final segment, or whether words containing the "in-" prefix are stored as fully derived forms, in which case the assimilation process is purely historical (Baldi, Broderick, & Palermo, 1985; Bauer, 1983). In the only study which has assessed this experimentally, Baldi et al. (1985) showed that participants do assimilate the "in-" prefix when given novel forms, suggesting both that "in-" maintains a separate lexical representation as a prefix, and that the assimilation process is active in the English lexicon.

In contrast, other prefixes in English do not exhibit these kinds of alternations, despite very similar contextual environments. Compare the alternation of "in-" with the "un-" prefix. Both prefixes are used to negate the stem to which they are attached, both consist of a vowel with a following nasal segment, and both are very frequent and productively used. Even so, the "un-" prefix is not required to assimilate, thus speakers produce forms such as "unpredictable", "unlikable", "unmastered" and "undeniable", all of which utilize the coronal nasal [n]. There is, however, an optional assimilation process which "un-" participates in which does result in assimilation before labial stems (e.g. before [m], [b], and [p]). Hence both "u[n]prepared" and "u[m]prepared", with the assimilated nasal, are acceptable pronunciation variants in English. This type of assimilation is an active process and is thought to be relatively common, although the rate at which the assimilated "um-" is produced has not to our knowledge been quantified through any phonetic studies of contemporary usage. This assimilation process is thought to vary within single speakers, thus the same individuals who produce "u[n]predictable" in some contexts may produce "u[m]predictable" in others, suggesting not a regular assimilation process, but rather one driven by external factors such as the rate of speech or formality of usage.

The "in-" and "un-" prefixes, and their differing patterns of assimilation, have been conceptualised in a number of different manners in the linguistic literature. One approach is to suggest differences in the underlying specifications of the prefixes themselves. In this case, because "in-" alternates in a predictable manner, it is a prime candidate for lexically-bound underspecification. Following the conservative approach and underspecifying only those segments which predictably alternate, the stored form of "in-" would therefore lack specification for both nasality (to accommodate [l]/[r] stems) and place of articulation (to accommodate labial and velar stems). On the other hand, the alternation observed in "un-" varies within speakers and is not fully predictable, therefore the final segment in "un-" would be predicted to be one which fully specifies the coronal place of articulation, i.e. [n]. In some theories, notably Lexical Phonology (Mohanan, 1982), these two prefixes also belong to different lexical strata (with "in-" being a class I affix, and "un-" being a class II affix) which accounts for the differences in assimilatory behaviour. It is worth noting that this account is not necessarily in contrast to underspecification, as specific instances of Lexical Phonology often also include Radical Underspecification as a basic tenet (cf. Kiparsky, 1982; McMahon, 1992).

1.3. The current experiment

To test for differences in the underlying specification of the “in-” and “un-” prefixes, we developed an adapted version of the paradigm used by Lahiri and Reetz (2010) and subsequent FUL studies. We assume that listeners map phonetically detailed input stimuli onto stored representations which vary in the degree to which they are underspecified. To expand this paradigm for use in lexical contexts, we had subjects perform an error detection task and introduced modified versions of “in-” and “un-” prefixed words in which the prefix nasal had been altered. For “in-”, this resulted in items in which the wrong form of the prefix was used (e.g. “i[n]proper”, “i[m]tolerant”), violating required assimilation conventions. For “un-”, this same manipulation results in forms which either violated assimilation conventions by using a labial nasal before non-labial stems (e.g. “u[m]traditional”, “u[m]grateful”) or were appropriately assimilated variant pronunciations (e.g. “u[m]predictable”). We examine the behavioural and electrophysiological responses to modified compared to unmodified words to determine whether the altered nasal segments disrupt processing equivalently across these two prefixes. If alternation triggers underspecification, as has been suggested, we predict an asymmetrical response across the prefix patterns, which is particularly relevant in the comparison of non-labial stems (i.e. the responses to “u[m]traditional” compared to “i[m]tolerant”).

In previous underspecification studies which employ nonwords (e.g. Friedrich et al., 2006, 2008), N400 responses have been reported to mismatching stimuli, consistant with numerous previous studies finding N400 responses to nonwords (cf. Connolly & Phillips, 1994; Kutas & Federmeier, 2011; O’Rourke & Holcomb, 2002; Praamstra, Meyer, & Levelt, 1994). The current paradigm differs from previous studies as the stimuli used are both morphologically complex, and contain ungrammatical uses of prefix variants which engender violations of word formation rules. The LAN component has been shown to index morphosyntactic violations in a number of studies (Coulson, King, & Kutas, 1998; Friederici, 2002; Krott, Baayen, & Hagoort, 2006; Opitz, Regel, Müller, & Friederici, 2013; Rossi, Gugler, Hahne, & Friederici, 2005), although distinguishing LAN responses from N400 responses can be difficult, as the timing and distribution of these components varies signficiantly across studies. This issue is compounded by the fact that auditory stimuli are rarely used in studies of morphosyntactic violations. Of those using auditory stimuli, the onset of the LAN component has been shown to emerge early, prior to 200 msec after the onset of the critical disambiguating context (Hasting & Kotz, 2008; Shen, Staub, & Sanders, 2013), with a frontal distribution which is typically left lateralised, although in some cases may be more bilaterially distributed (Hasting & Kotz, 2008). N400 responses in auditory paradigms may also occur earlier than for written stimuli, although there is some disagreement about whether earlier N400 effects in auditory paradigms are in fact a distinct response (see Hagoort & Brown, 2000 for review). When present, however, the auditory N400 frequently presents with a cannonically central-posterior distribution (Friederici, Pfeifer, & Hahne, 1993; Perrin & García-Larrea, 2003). Thus the primary distinguishing feature of the N400 and LAN responses are found in the topography of the response in relation to the types of stimuli used.

We posit therefore that these items may elicit a LAN rather than an N400, although these responses may be graded by the degree to which participants treat our stimuli as containing violations of morphophonological word formation conventions, rather than as nonwords per se. Thus we predict that forms such as “u[m]tidy” should elicit a LAN and show good error detection rates, as these items should result in a “mismatch” between the surface labial and underlying specified “un-” prefix. On the other hand, if “in-” is underspecified, using the wrong form of the prefix should result in a “no-mismatch” situation, as neither [m] nor [n] conflict with the specification of the prefix. For “in-” then, we predict poor error detection and no LAN response for the modified stimuli. Finally, the use of variant pronunciations such as “u[m]predictable” should be rapidly accommodated, as has been shown for this type of coarticulatory assimilation in previous work (Gaskell & Marslen-Wilson, 1996, 1998; Mitterer & Blomert, 2003). For these items, we predict no LAN and poor error detection. The predictions are summarised in Table 1.

2. Experimental methods

2.1. Stimuli

Using the Celex corpus (Baayen, Piepenbrock, & Gulikers, 1995), 60 “in-” and 60 “un-” prefixed items were chosen which represented an even distribution across major places of articulation: 20 labial stems, 20 coronal stems, and 20 velar stems. The items were matched in overall frequency, written frequency, and spoken frequency in the Celex corpus, and in the scaled million-word Celex corpus (see Table 2). However, there was a significant difference in length (measured by number of syllables) across the prefixes, as “in-” items with non-labial stems tend to be somewhat longer. A set of 120 filler items were also drawn from the Celex corpus and matched to the experimental stimuli in frequency, number of

Table 1. Examples of nonword stimuli and processing predictions.

Prefix	Stem	Example input	Stored form	Mapping	Predictions
IN-	labial	i[n]precise	underspecified	no-mismatch	Poor error detection no LAN
	coronal	i[m]tolerant	underspecified	no-mismatch	Poor error detection no LAN
	velar	i[m]capable	underspecified	no-mismatch	Poor error detection no LAN
UN-	labial	u[m]prepared	specified [n]	no-mismatch*	Poor error detection no LAN
	coronal	u[m]traditional	specified [n]	mismatch	Good error detection LAN
	velar	u[m]critical	specified [n]	mismatch	Good error detection LAN

Notes: The asterix listed for the labial UN stimuli indicates that these items, by virtue of being familiar pronunciation variants produced by a productive assimilation process in English, are not true nonwords. Therefore, we do not predict a mismatch in this case, as the variant pronunciation of these items will be accomodated for in perception.

syllables, lexical category, and overall morphological structure (complex derived word forms beginning with a prefix). See Lawyer and Corina (2017) for further discussion of the stimulus set.

Nonword stimuli were created from the word stimuli by changing the place of articulation in the nasal segment of the "in-" and "un-" prefixes. The prefix-final nasals which in real words contained an [n] were changed for an [m], and any which originally had an [m] were changed for an [n]. This results in forms such as the nonword "i[m]capable" from *incapable*, or "u[m]conscious" from *unconscious*. Nonword filler items were created by introducing a number of alterations to a novel set of 80 real words. Half ($N = 40$) include only a change to a single major feature category (such as "bilateral" becoming "binateral"), and half ($N = 40$) include a change to a single segment (such as "remodel" becoming "rezodel"). Alternations in the nonword filler stimuli effect primarily consonants located in prefixes or near the beginnings of the words, mimicking the structure of the experimental stimuli.

Both experimental and filler stimuli were recorded by a male speaker of California English. In order to avoid list intonation effects and maximise natural prosodic patterns, all words were put into a randomly generated sentence frame ("The word __ is (adjective)"). Nonword filler stimuli were practiced and spoken in the same manner as word stimuli, as were a number of additional items beginning with "um" which were used as the basis for splicing experimental nonword stimuli (discussed further below). Each item was elicited three times from each speaker, and a best token selected based on auditory assessment by the researcher and analysis of each spectrogram in Praat (Boersma & Weenink, 2011). The selected tokens from both speakers were normalised for amplitude in Praat.

The experimental nonword stimuli (e.g. "u[m]believable") were created by splicing prefixes onto word stems using Praat and Audacity software. In order to maintain naturalistic speech stimuli, the spliced prefixes were extracted from real words. A single "in-" and "im-" example were selected from the already recorded experimental stimuli (e.g. "improbable", "intolerant"). As no prefixed words containing the "um-" allomorph were elicited, these items were taken from "umpire" and "umbrella", which were included in the original recording list. In all cases, the splices occurred at zero crossings and the quality of each splice was assessed by the researcher auditorily and spectrally to verify the nonword stimuli were correctly constituted. See

Table 2. Summary of stimulus metrics comparing over all frequency, written frequency, and spoken frequency as reported in the Celex corpus. No statistically significant frequency differences are found in the experimental stimuli. Syllable count is also included as a measure of length, and shows a significant difference between test items. Posthoc testing reveals that velar and coronal IN are longer than the other stimulus groups, but that there are no significant differences within UN stimuli or between these and labial IN items.

		Frequency	Written frequency	Spoken frequency	Syllable count
IN-	labial	59.40 (11.30)	57.75 (11.16)	1.65 (0.43)	3.50 (0.19)
	coronal	55.75 (13.05)	54.25 (12.87)	1.50 (0.37)	4.20 (0.20)
	velar	74.85 (18.68)	71.25 (17.33)	3.60 (1.60)	4.10 (0.16)
UN-	labial	59.10 (19.04)	56.75 (17.84)	2.35 (1.30)	3.55 (0.18)
	coronal	51.80 (22.39)	49.75 (21.27)	2.05 (1.17)	3.60 (0.15)
	velar	65.10 (19.16)	63.55 (18.71)	1.55 (0.67)	3.60 (0.26)
	$F(5, 114)=$	0.21	0.20	0.60	2.55
	$p=$	0.96	0.96	0.70	0.03

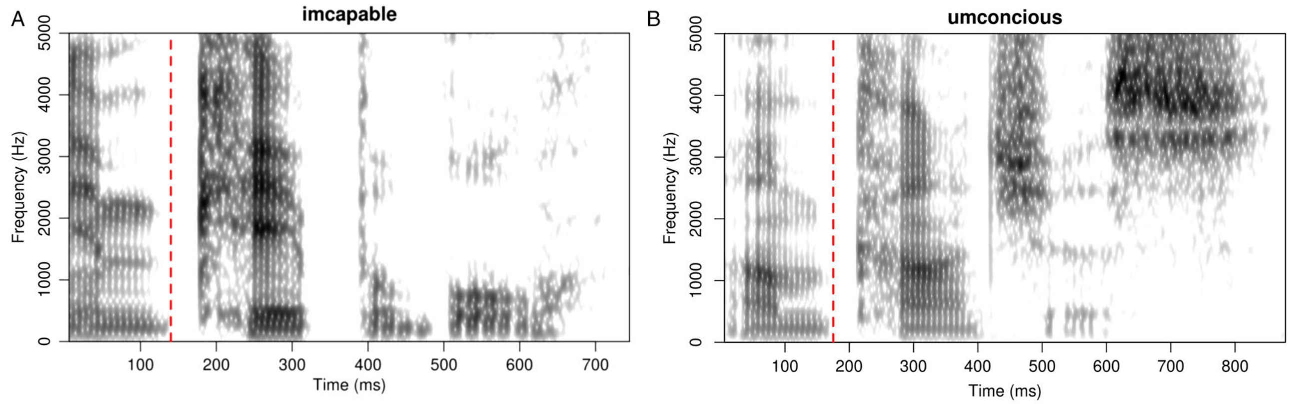

Figure 1. Spectrograms of example nonword stimuli (A) "imcapable" and (B) "umconscious". The red dashed line indicates the boundary between the spliced "im-" and "um-" prefixes and the root words.

Figure 1 for example nonword spectra which illustrate prefix splice points.

2.2. Subjects

Thirty-six subjects (24 female) participated in this experiment. Prior to beginning the experiment, subject consent was acquired, as required by the regulations of the Institutional Review Board of UC Davis. Each subject completed a background form which detailed their language experience, including bilingual status, and handedness. A total of 17 subjects reported being bilingual, and six were left-handed. Any subject who had a history of hearing problems, neurological issues, or was not a native speaker of English (defined as having learned English prior to the age of 5) was excused from participation.

2.3. Data collection

EEG data was acquired using a 32-channel Biosemi ActiveTwo system, with additional electrodes attached above, below and at the outer canthus of the left eye to monitor the electrooculogram. Impedance threshold values were kept below 20 kΩ. The signal was referenced to the average of the left and right mastoids, and sampled online at 512 Hz.

Subjects were comfortably seated in a small climate-controlled, sound-attenuated room. Stimuli were presented over a single high quality speaker (Epos ELS-3C) at approximately 65 decibels using Presentation software (Neurobehavioral Systems Inc., 2014). During the experiment, subjects fixated on a white cross projected on an LCD monitor, which also provided instructions and alerted subjects to the beginning of the trial. Subjects were asked not to blink while the white fixation cross was present to reduce the occurrence of ocular artefacts during critical trials. After each stimulus item was played, subjects were asked to withhold word/nonword responses until prompted, at which point they responded with a keyboard button press. Due to the length of the experiment, stimuli were broken into three blocks of approximately 10 min duration and subjects were given a rest period after each.

A vocabulary test (Brown, Fishco, & Hanna, 1993) was administered following the EEG portion of the experiment. Subject vocabulary scores were included as a factor in the response accuracy models (discussed below).

2.4. Data analysis

Six subjects were removed from analysis: three because of performance issues during the experiment (i.e. falling asleep), and a further three had 25% or more of individual trials contaminated by artefacts. The remaining data from 30 subjects was pre-processed using the EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes in MATLAB (The MathWorks, n.d.). The data was downsampled to 256 Hz, and bandpass filtered between .1 and 30 Hz offline. Artifact rejection occurred in two stages. First using EEGLAB's binica algorithm for independent component analysis (ICA), blink and horizontal eye movement components were manually identified and removed from the data. For all subjects, these were within the first six available components, and no more than three components from among these were removed for any subject. A second pass at artefact rejection used voltage thresholds (typically 120 Hz in scalp channels, and 60 Hz in external (ocular) electrodes) to identify epochs containing additional artefacts which were not removed during ICA. Subjects who had a artefact rejection rate of greater than 25% during the second pass were discarded. The data from the 30 remaining subjects was epoched from −200 ms before to 1400 ms after the onset of each stimulus item, with the prestimulus period (−200 to 0 ms) used for baseline correction. ERPs were calculated for each combination of prefix category (IN/UN), stem place (labial/coronal/velar) and lexical status (word/modified).

2.5. Statistical methods

Classification accuracy was analysed for each subject using a mixed-effects logit model as outlined in Lawyer and Corina (2017). Due to computer error, only a subset of subject responses were correctly logged. Therefore the analysis of classification accuracy contains responses from only 16 subjects (53% of the total data). Note that as subjects were asked to withhold their responses until a specified point following stimulus presentation, response latency was not analysed.

The accuracy model was initially estimated with a maximal fixed effects structure, including factors for Lexical status (word/modified), Prefix (IN/UN), Stem (labial/coronal/velar), Sex (M/F), Age, Handedness (L/R), ResponseHand (L/R), VocabularyScore, BilingualStatus (Y/N), Trial, Length (in msec), Frequency, StemFrequency, and UniquenessPoint (in msec). Continuous variables were scaled and centred, and log transformed where appropriate to approximate a normal distribution and reduce potential colinearities. As Frequency and StemFrequency measures are somewhat correlated ($r = .23$), StemFrequency was residualized against Frequency. Using an iterative pruning method, individual factors which did not surpass a threshold z-value of 2 were removed and the model was refitted until only significant factors remained. The model also included a maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013), including by-item and by-subject random intercepts. Inclusion of these random effects were justified via loglikelihood comparisons to models which did not contain these factors.

Electrophysiological responses were analysed as ERP difference waves, constructed by subtracting responses to nonwords from real words within each stimulus category (i.e. difference waves for coronal UN stimuli indicate where responses to nonwords such as "umtenable" diverge from real words such as "untenable"). Statistical analysis of the ERP difference waves was performed in two windows: an early window, 170–250 msec, centred around the observed P2 peak differences across stimulus categories, and a later window, 250–750 msec, to capture potential LAN/N400 effects. This later window was defined based on a separate analysis of the filler word and nonword responses which showed a large negativity for nonwords relative to words in this time period.

Statistical evaluation of the ERP difference waves used a cluster mass permutation test as implemented by the Mass Univariate toolbox in MATLAB (Groppe, Urbach, & Kutas, 2011; The MathWorks, n.d.). This method allows for the testing of significant differences between conditions at all electrode sites and all desired time points simultaneously. This treatment of ERP data has been suggested as an improvement over more standard repeated measures ANOVAs for a number of reasons. Among the more compelling is the electrophysiologically valid addition of clustering, which acknowledges that ERP components should be detected in not just a single electrode, but rather in a cluster of adjacent electrodes at any particular time point. In addition, statistical tests which use clustering and permutation have been shown to be good at discerning broad events, such as N400 responses, particularly if the exact time course of the component is less relevant than its presence or absence (see Groppe et al., 2011 for thorough discussion).

The cluster-based tests used here are repeated measures permutation tests which use cluster mass to constrain the analysis and correct for the large number of comparisons carried out, holding the familywise error rate below an alpha level of 0.05. The permutation algorithm creates 2500 random within-subject permutations of the available data and clusters together all t-scores above 0.05 (uncorrected) with t-scores from neighbouring electrodes within a 6.29 cm radius (a total of 3–6 neighbours per electrode site). Significance is determined by comparing the acquired data to the null distribution derived from the permuted data for each cluster. In evaluation of amplitude differences in the early time window, two-tailed tests were used as there was no prediction about the direction of the potential ERP effect (whether modified stimuli would increase or decrease P2 amplitude). In the later time window, one-tailed tests were used to look specifically at decreases in ERP amplitude congruent with LAN/N400 responses.

3. Results

3.1. Behavioral

3.1.1. Words

Within real words, accuracy was high over all, with subjects correctly identifying on average 87% (SEM = 1%) of items as real words. In the mixed-effects model, a number of factors significantly predicted accuracy, the largest of which was word frequency, with more frequent words having higher accuracy (OR: 1.94, $z = 2.70$, $p < .01$).

Table 3. Summary of accuracy data for words and nonwords.

		Words		Nonwords		
		mean	sem	mean	sem	d'
IN-	labial	83.75	2.93	26.25	3.49	0.34
	coronal	87.36	2.47	34.71	3.66	0.75
	velar	84.57	2.85	30.46	3.50	0.51
UN-	labial	92.50	2.09	13.12	2.68	0.32
	coronal	87.50	2.62	44.38	3.94	1.01
	velar	89.57	2.16	21.18	3.14	0.58

Accuracy also increased with subject age (OR: 1.32, $z = 4.49$, $p < .0001$) and bilingual status (bilingual subjects were more accurate, OR: 2.07, $z = 2.82$, $p < .005$). There was no statistically significant difference in Stem or Prefix categories, and no significant Stem x Prefix interaction (all p-values greater than .05). Average responses by Prefix and Stem are listed in Table 3 and illustrated in Figure 2.

3.1.2. Nonwords

Within the nonword stimuli, accuracy was quite low (mean = 28%, SEM = 1.4%), with poor signal detection ($d' = 0.60$) suggesting subjects had difficulty discriminating nonword stimuli from real words in general. However, accuracy did vary across stimulus categories, evidenced by a significant Prefix x Stem interaction ($\chi^2(2, N = 994) = 10.99$, $p = .004$) in the mixed-effects model. A number of additional factors significantly predicted nonword identification, including the original word's frequency. The more frequent the word from which the stimuli were derived, the more likely subjects were to identify the item as a real word (OR: .55, $z = -4.41$, $p < .0001$). Subjects also showed a modest improvement in accuracy over the course of the experiment (OR: 1.40, $z = 3.69$, $p = .0002$). No other factors were significant in the nonword model.

Post-hoc testing using least squares means with Tukey's adjustment for multiple comparisons showed that the Prefix x Stem interaction effect was driven by particularly poor performance on labial UN items such as "u[m]predictable" (mean = 13%, $d' = 0.32$) relative to other stimulus categories (mean for coronal UN = 44%, $d' = 1.01$, $z = -5.47$, $p < .0001$; mean for labial IN = 26%, $d' = 0.35$, $z = 3.51$, $p = .006$; mean for coronal IN = 35%, $d' = 0.75$, $z = 4.81$, $p < .0001$; mean for velar IN = 30%, $d' = 0.51$, $z = 4.46$, $p = .0001$). However, there was no statistically significant difference between performance on labial UN items and velar UN items such as "u[m]conscious" (mean for velar UN = 21%, $d' = 0.58$, $z = -2.38$, $p = .16$). While responses to velar UN items were also not found to be different from those any of the IN stem categories, they were significantly less accurate than responses to coronal UN items such as "u[m]deniable" ($z = 3.37$, $p = .01$).

3.2. ERP

Visual inspection of the ERP data shows that in all stimuli, including fillers, an initial negativity (N1) is present which peaks around 160 ms and is strongest in posterior electrode sites. Following this, there is a large positive peak

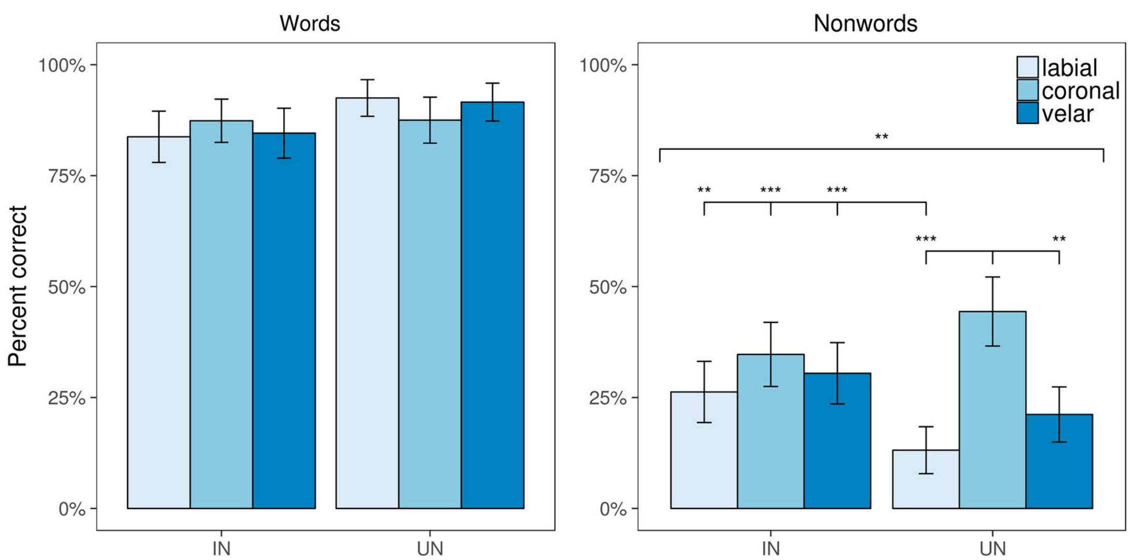

Figure 2. Mean accuracy for word and nonword responses. No statistically significant differences are found among word responses. In nonwords, a significant interaction between Prefix and Stem is observed ($F(2,984) = 10.99$, $p = .004$). Responses to labial UN stimuli were less accurate than coronal UN ($p < .0001$), labial IN ($p = .006$), coronal IN ($p < .0001$) and velar IN ($p = .0001$) stimuli. Additionally, velar UN stimuli were less accurate than coronal UN stimuli ($p = .01$). There were no statistically significant differences between among the remaining Prefix and Stem categories.

(P2) at 260 ms which is maximal over lateral anterior electrode sites. At approximately 350 ms, a broad negativity begins which is larger for nonwords than for words, and plateaus at approximately 700 ms in anterior electrode sites.

3.2.1. Early window

In the early window (175–250 msec), analysis of difference waves shows significant changes in amplitude for some but not all stimulus categories. Specifically, for the IN prefix an increase in amplitude is observed for labial stems (i.e. P2 amplitude is larger for modified forms such as "i[n]proper" than for "i[m]proper"). This positivity was significant in a single cluster (corrected $p = .013$) encompassing bilateral frontal electrodes (Fp1, Fp2, AF4, F3, F4, F7, F8, FC1, FC2, FC5, FC6, C3, C4, T7 and T8). No significant differences in amplitude were observed for coronal or velar IN categories.

In the UN prefix set, both labial and velar categories showed decreases in amplitude (i.e. P2 amplitude was smaller for forms such as "u[m]predictable" and "u[m]conscious" than for "u[n]predictable" and "u[n]conscious"). For labial stems, this reduction was significant in a single cluster (corrected $p = .006$) encompassing bilateral frontal electrodes (Fp1, Fp2, AF3, F3, F4, F7, F8, FC1, FC2, FC6, C3, C4, T8, CP1 and CP6). In velar stems, the reduction is observed in a single cluster (corrected $p < .0001$) involving nearly all scalp electrodes. Electrodes *not* included in the significant cluster are only (Fp1, F7, F8, and PO3); remaining sites showed significant decreases in amplitude to modified velar UN stimuli. No significant differences in amplitude were observed for coronal UN stimuli (i.e. P2 amplitude was equivalent for forms such as "u[m]tenable" in comparison to "u[n]tenable"). See Figure 3 for illustration.

3.2.2. Later window

In the later window (250–750 msec), analysis of difference waves found significant decreases in amplitude for modified stimuli in both prefix categories. Within the IN prefix, this decrease was observed only for coronal stems (i.e. "i[m]tolerant") and found in a single broad cluster (corrected $p = .005$) encompassing occipital, midline, and frontal sites (see Figure 4 for illustration of significant electrodes included in the cluster). Two local maxima are observed in the clusters. The first is centred at 335 msec, with largest *t*-values in sites O1 ($t(1, 29) = -.4.52$), O2 ($t(1, 29) = -4.77$) and Pz ($t(1, 29) = -4.84$). A second local maximum is found at approximately 400 msec, with largest t-values again in sites O1 ($t(1, 29) = -.4.25$), O2 ($t(1, 29) = -4.22$) and Pz ($t(1, 29) = -4.15$). No significant decreases in amplitude were observed for labial or velar IN items (i.e. responses to "i[m]capable" and "i[n]proper" were not more negative than for "i[n]capable" and "i[m]proper" in this window).

For the UN prefix, significant decreases in amplitude were observed in both coronal and velar stems. In coronal items (e.g. "u[m]tenable"), this was restricted to a single significant cluster which reached significance

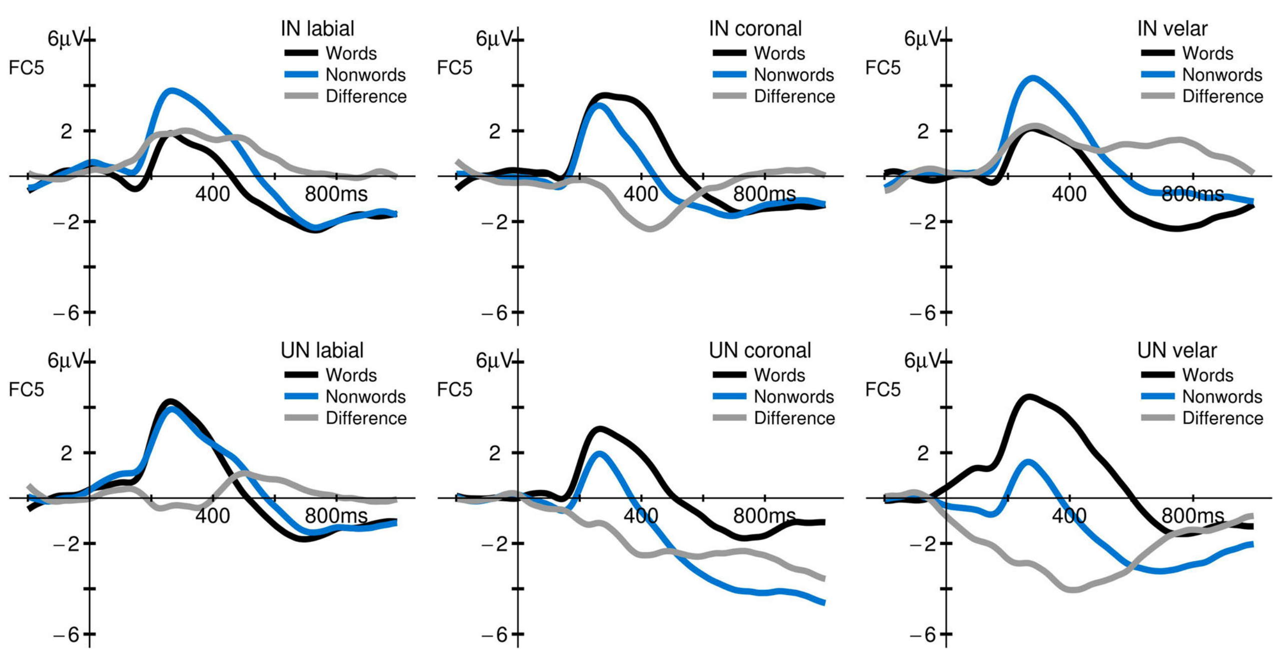

Figure 3. Averaged ERP responses and difference wave at site FC5 for each Stem and Prefix category.

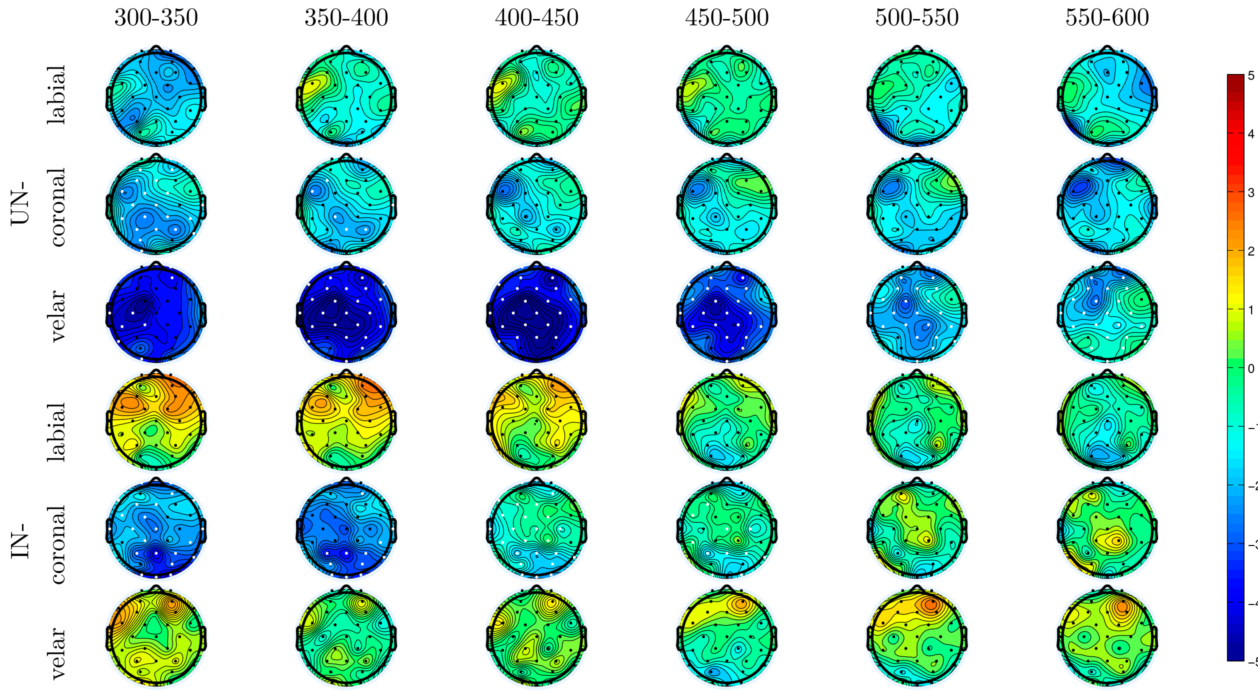

Figure 4. Scalp topographies illustrating the difference between word and nonword responses for each Prefix and Stem category, from 300 to 600 msec, with mean amplitude averaged over 50 msec bins. A significant negative deflection was observed in left anterior sites in coronal ($p = .04$) and velar UN ($p < .0001$) items. Coronal IN items also showed a significant negative deflection ($p = .005$) with a primarily occipital focus which is not observed in the remaining stimulus categories. Individual electrodes are highlighted in white for each time window where they provided a significant contribution to the observed clusters. Electrodes which did not contribute to the significant clusters are in black.

between 350 and 450 msec (corrected $p = .04$). Included in this cluster are left and right anterior sites, right posterior sites, and central and midline sites. Maximal t-values were observed in left anterior sites, with the largest response in site FC5 at approximately 390 msec ($t(1, 19) = -4.41$).

For velar items (e.g. "u[m]conscious"), difference waves revealed a large discrepancy between modified stimuli and real word responses, resulting in a significant cluster which encompasses nearly all electrode sites. This cluster maintained significance from 250 through 700 msec (corrected $p < .0001$), although within this large window, several local maxima are observed. The most significant local maximum is found in site FC5 at approximately 450 msec ($t(1, 29) = -4.15$) and 600 msec ($t(1, 29) = -5.19$). There are additionally several other local maxima observed earlier in site AF4 at approximately 400 msec ($t(1, 29) = -3.90$) and in site Cz at 540 msec. ($t(1, 29) = -4.17$) and 650 msec ($t(1, 29) = -3.92$).

There was no significant decrease in response amplitude for labial UN items in this later window (i.e. responses to "u[m]predictable" were not more negative than "u[n]predictable").

The timing and topography of response to coronal UN items, and a portion of the responses observed for velar UN items (particularly the maxima in FC5 around 450 msec), are consistent with a left anterior negativity (LAN) component. This observation is supported by analysis of scalp topographies of the difference waves (see Figure 4) as well as in comparison of the raw responses to modified words (see responses in Figure 5 beginning at 450 msec). Both of these Figures illustrate the localised left anterior negativity in coronal and velar UN items which is not found in the other stimulus categories during this 400–450 msec time window.

4. Discussion

In this study we asked what effect altering the form of "in-" and "un-" prefixes would have on electrophysiological and behavioural responses in a mispronunciation detection task. We predicted that responses to modified IN and UN prefixes would not be symmetrical, as only IN was suggested to have an underspecified lexical form due to its predictable and regular pattern of morphophonological alternation. Our data supports this claim, showing that responses to modified UN prefixes resulted in larger and more sustained negativity than in the modified IN stimuli. This effect is evident only in coronal and velar stems, and is particularly strong in left anterior electrode sites, peaking around 400–450 msec. IN items appear to be less sensitive to the selection of appropriate

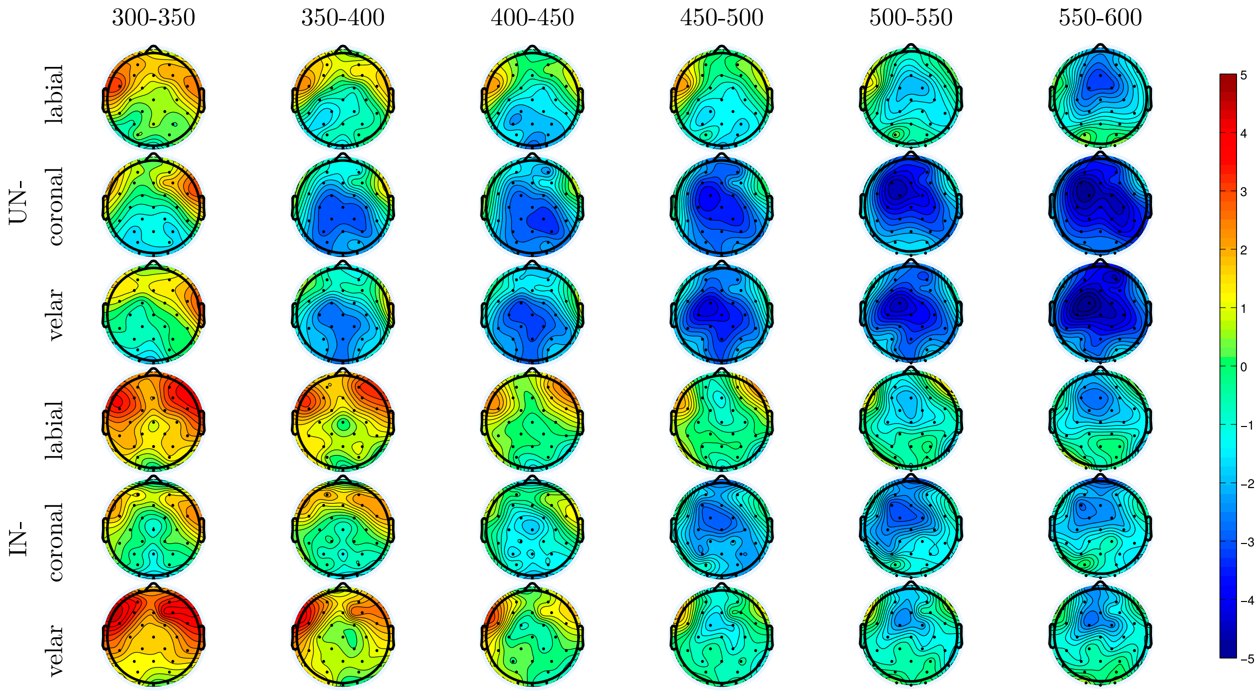

Figure 5. Scalp topographies illustrating nonword responses for each Prefix and Stem category, from 300 to 600 msec with mean amplitude averaged over 50 msec bins. Visible is the negativity in coronal and velar UN responses is focussed in left anterior sites beginning at approximately 450 msec.

prefix forms when compared to the UN forms, which is consistent with predictions made following an account of lexically-based underspecification.

The behavioural responses to the modified stimuli also showed an asymmetry between IN and UN prefixes, although they do not provide a perfect analogue to the observed ERP responses. In particular, responses to IN stimuli were overall more accurate than responses to UN stimuli, with the exception of the coronal UN items. It is not uncommon for ERP responses to be more sensitive to certain experimental manipulations than behavioural responses, particularly in a case such as this where ERP responses are time-locked to the onset of the critical stimuli, but behavioural responses are withheld for a specified period. Indeed, in previous behavioural experiments in our lab, speeded error detection using these stimulus items resulted in very poor nonword identification rates for IN stimuli (Lawyer & Corina, 2017), in addition to the poor performance on the labial UN stimuli replicated here.

4.1. The LAN component

In the original set of predictions, we suggested the topography of the ERP response would be dependent on the degree to which subjects would treat the modified forms as nonwords compared to items which violated requirements on morphological structure. The response we observe in the modified velar and coronal UN stimuli shows a left anterior distribution, consistent with the typical topography reported for a LAN component. On the other hand, the brief negavitity observed for coronal IN items was both earlier (330–400 msec) and centred in occipital sites O1/O2, a response profile which does not have precedence in either the LAN or N400 literature to our knowledge. Responses to the modified IN stimuli, while distinct from those for real words, do not appear to reflect the same processing mechanisms engaged with the modified UN stimuli. What this may reflect is a question for further inquiry.

The timing and topography of the electrophysiological response to modified UN items is in line with previous accounts reporting a LAN component in experiments with morposyntactic manipulations (for instance, in cases of subject-verb agreement violations: see Roll, Groselke, Lindgren, & Horne, 2013; Rossi et al., 2005). In the present experiment, the stimuli used existing forms of the “in-” and “un-” prefixes in phonological contexts where they are not typically found. These context violations are however not tied to further syntactic or semantic violations, as the grammatical information present is unchanged. The LAN observed here appears to be sensitive to contextual incongruencies based on the phonological form alone, separate from syntactic or semantic violations. This expands on data presented by Krott et al. (2006), who observed increased LANs related to incorrect plural suffix selection in Dutch. However, in this case, a LAN is observed even in derivational contexts, where form selection is dictated solely by morphophonological considerations.

4.2. Effects of lexicality

It is worth considering the degree to which the results observed here depend on comparisons between words and modified forms in each case. For the labial UN stimuli, this issue is complicated by the fact that the modified forms exhibit a familiar and frequently observed pattern of coarticulatory assimilation in natural speech. It is not surprising that these modified forms did not result in a detectable "error" response in this study, supporting our prediction that these items would function analogously to "real" words. This finding is also consistent with previous studies which have shown that predictable phonetic assimilations are rapidly accommodated during online speech perception (Gaskell & Marslen-Wilson, 1996, 1998; Mitterer & Blomert, 2003). The behavioural data provides additional support for this analysis, as error detection accuracy in these forms is remarkably low, and further replicates previous findings in our lab which used these stimuli in a speeded lexical decision task (Lawyer & Corina, 2017).

The question of lexicality is of greater importance in the interpretation of the remaining IN and UN items. To address whether asymmetries existed within these items separate from considerations of lexicality, we ran an additional post-hoc analysis comparing just the responses to modified IN and UN stimuli, paired by place of articulation (e.g. comparing coronal IN to coronal UN responses, and velar IN to velar UN responses). The original analysis, then, can be seen to represent the effects of modification within each prefix-stem pairing, whereas this posthoc analysis looks directly at the effect of prefix within each stem class in modified forms alone. Statistical methods in this section are identical to those of the primary analysis (employing a cluster premutation test on difference waves, in earlier (170–250 msec) and later (250–750 msec) time windows). Note that because of the considerations laid out above, labial items were not included in this analysis as labial IN and UN items differ both in terms of prefix and lexicality.

In this secondary analysis, we again find significant differences between IN and UN prefixes, showing UN responses to be more negative. In the early window, this difference was significant in coronal items in a single cluster from 180–240 msec in central channels bilaterally (adjusted $p = .002$), with largest t-values observed at 219 ms in site C3 ($t(1, 29) = -4.839$) and at 215 ms at site CP2 ($t(1, 29) = -4.59$). For velar items, a single significant cluster was found encompassing frontal, central, and parietal channels from 180–250 msec (adjusted $p < .0001$), with local maxima centred in cite F3 at 223 ms ($t(1, 29) = -4.58$) and PO3 at 242 ms ($t(1, 29) = -4.44$). For the later time window, significant differences between IN and UN responses are found in velar items only. This difference is located in a single cluster encompassing frontal and central channels bilaterally from 280–480 msec (adjusted $p = .008$), with maximum t-values observed in site FC5 at 379 ms ($t(1, 29) = -4.94$) and 449 msec ($t(1, 29) = -4.50$). A comparison of resposnes to modified IN and UN items are illustrated in Figure 6.

This finding adds to the previous data showing asymmetries in the responses to IN and UN stimuli, although it is noteworthy that the strongest difference between IN and UN prefixes when directly compared is in the earlier time window. It is possible this secondary anaylsis serves to highlight the more phonological aspects of this manipulation, as P2 amplitude changes have been shown in previous studies to mark changes in phonotactic probability or phototactic neighbourhood density. Previous research has shown that words with low phonotactic probability densities have smaller amplitude P2

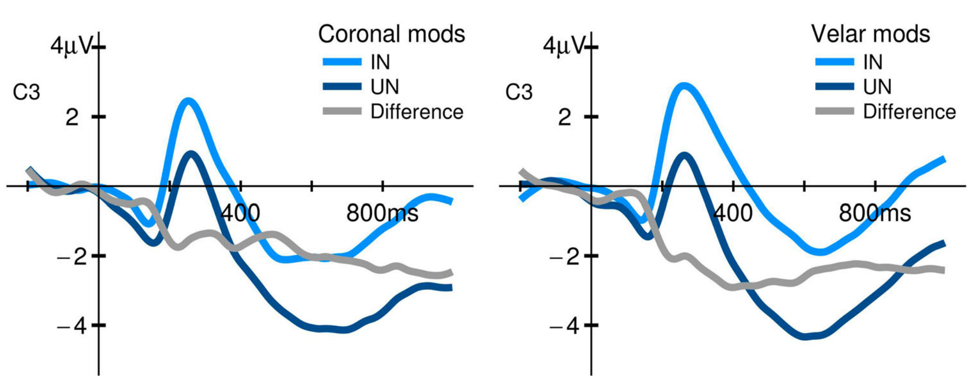

Figure 6. Averaged ERP responses and difference wave showing modified IN and UN stimuli for coronal and velar stems, plotted at site C3.

responses than words with high phonotactic probability densities (Hunter, 2013; Rossi, Hartmüller, Vignotto, & Obrig, 2013 though see also Cheng, Schafer, & Riddell, 2014). The results obtained here do not directly support these claims, as differing P2 responses are observed to stimuli with equivalent phonotactic probabilities (particularly the zero-probability of both [im+k/g] and [um+k/g] sequences). More work is needed to elucidate which stimulus features reliably modulate P2 amplitude in phonological and morphophonological paradigms.

4.3. Underspecification and models of lexical storage

The pattern of results observed here are consistent with a view of the lexicon which includes underspecification triggered by predictable alternations. It is not, however, immediately compatible with previous work within the FUL paradigm which has shown in numerous studies that coronal segments are underspecified for place. Both "in-" and "un-" prefixes end in coronal nasals, and thus, FUL would not predict the asymmetries we observe here. It is worth considering the fact that the majority of the previous FUL studies have used single sounds and nonword syllables in MMN paradigms. There is the possibility that the effects observed here, which are lexically specific, may recruit different mechanisms during speech perception, distinguishing lower-level phonetic mapping procedures from those which interact with lexical information. How these two processes may be integrated warrants further investigation.

It is worth noting that the results presented here, particularly with reference to the labial UN stimuli (e.g. "u[m]predictable"), are also consistent with models of the lexicon which do not explicitly include underspecification. In particular, these results are consistent both with sparse lexical accounts and extremely rich lexical accounts, including usage-based theories which employ exemplars as the basic unit of lexical storage (e.g. Bybee, 2003; Johnson, 2007; Sumner & Samuel, 2005). When using morphophonological alternations, the possibilities for adjudicating between these theories are not many, and the current study cannot distinguish between these theories.

This conflation of predictions made by opposing models is not accidental, but rather the consequence of both sets of theories seeking to model the same phenomena: that lexical access is achieved in the face of variation. Morphophonological alternations offer an example of a particularly salient type of variation, involving entire segments which exist as independent phonemes elsewhere in the language (i.e. [n]/[m]). Alternation-based underspecification chooses to omit information in the lexicon in this case, whereas usage-based theories may resort to using less strictly defined prototypes for the lexical items in question (Bybee, 2010). A prototype which does not contain a strong prediction about the character of the nasal in the "in-" prefix is therefore not broadly distinguishable from one which omits the information about place of articulation via underspecification. Through differing mechanisms, both theories arrive at the same conclusion: in the case of variation, the lexicon may not make strong claims, whether through underspecification or through diminished prototype specificity, about the character of the sounds in question.

5. Conclusions

Several important findings emerge from this study. First, the data presented here provide evidence that phonological context plays a determining role in underspecification. In particular, morphophonological alternations which are predictable based on surrounding context are shown to be more tolerant to variation in the speech signal. While this data supports the general idea of sparse lexical forms, it does not show effects which are specific to coronal segments, as predicted by FUL. Second, this paper demonstrates that LAN effects may be observed even in cases where syntactic violations are not present, illustrating instead that violations of affix selection based purely on phonological grounds are sufficient to trigger a LAN response. Finally, this study adds to an emerging literature exploring the relationship between phonotactic probability and early ERP effects, such as the P2. In this study, phonotactic probability was not shown to modulate P2 amplitude as has been previously suggested.

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