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How the brain responds to possible and impossible words: an MMN investigation of wordhood in English

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ABSTRACT

Pseudowords and nonwords have served as cornerstones of psycholinguistic and neurolinguistic research, allowing researchers to examine language processing in the absence of lexical-semantic activation. To examine how graded phonotactic violations modulate pseudoword processing, we employed an auditory oddball mismatch negativity (MMN) paradigm with independent comparisons among four English stimuli ranging from phonotactically licit forms to combinations impossible in English: [kreɪlz], [kreɪlz], [kreɪls] and [kreɪls]. Importantly, such violations are not only reducible to the effects of individual segments but also arise from the interaction between vowel quality and word-final structure. We observed asymmetric MMN responses consistent with these combinatorial constraints, particularly for forms whose phonological patterns implied morphological structure. Robust MMNs occurred whenever the maximally illicit form served as the deviant, indicating strong perceptual conflict. Together, our findings reflect a cognisance of multiple phonological and morphophonological constraints, rather than a simple distinction between possible and impossible words.

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1. Introduction

Pseudowords and nonwords have served as cornerstones of psycholinguistic and neurolinguistic research, allowing researchers to examine language processing in the absence of lexical-semantic activation. Traditionally, pseudowords have been defined as “irregular or unfamiliar words”, i.e. pronounceable constructions that follow a language’s phonological and orthographic rules but do not exist in the language’s lexicon, e.g. **blick*¹ in English. In contrast, nonwords (or “nonsense words”, “illegal words”) contain strings of letters or sounds that cannot exist in the language, resulting in the word being partly or entirely unpronounceable, e.g. ***blzkw*. In many cases, the classification of these forms is based on assumptions about how a stimulus is likely to be processed (i.e. visually versus auditorily) rather than on its full linguistic properties. Definitions typically emphasise orthographic legality, yet a string that appears novel in written form may correspond to a real word when pronounced aloud; see, for example, *hart*, *tike*, *lare*, *hich*, *cort*, *rold*, *dold* (Stark & McClelland, 2000).

However, wordhood is not only based on what a language’s phonemes are and how they contrast, but

also on what is **an allowable** combination of sounds and contrasts (i.e. phonotactic constraints). For example, **blick* is more acceptable as a possible English word than ***bnick* because the initial consonant cluster /bn/ cannot occur in a word-initial position in the language. Critically, certain combinations of sounds can also trigger productive morphological processes, even in nonwords (cf. Berko, 1958). This issue is particularly relevant for stimuli ending in /s/ or /z/: in English, these segments are strongly associated with productive inflectional morphology (i.e. plurality). This raises a fundamental question in regard to processing: to what extent are pseudowords “possible” and nonwords “impossible”? Could their linguistic well-formedness (or malformedness in the case of nonwords) bias the very processes they are meant to isolate? As part of our general intuitions about our language(s), all native speakers have a notion of what a word is and what a possible word can be. This intuition, which is a part of every speaker’s core knowledge of their language, is tied to information that has been embedded in phonological, morphological, and semantic cues of the language itself.

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Neurolinguistic research (cf. Carreiras et al., 2007; Coch & Mitra, 2010; Mitterer & Blomert, 2003; Proverbio & Adorni, 2008) has indicated that neural responses to pseudowords and nonwords are mediated by an intuitive sense of “wordhood”. EEG (electroencephalography) studies have shown that both pseudowords and nonwords elicit different neural responses when compared to real words, particularly for ERPs (event-related potentials) related to lexicality (e.g. a larger N400; see Coch & Mitra, 2010), orthographic legality (N200; see Grossi & Coch, 2005), and even semantic familiarity in sentence processing (P600; see Huang et al., 2021). Critically, these effects have differed depending on whether the comparison is between a pseudoword (e.g. **darpel*) and a real word (*carpet*), or a pseudoword (**darpel*) and a nonword (***drgxem*).

This study probes native speakers’ intuition for wordhood through a series of electrophysiological brain measurements designed to elicit the mismatch negativity response (MMN). We employed an auditory oddball paradigm with four independent, a priori comparisons between pseudo- and nonword stimuli: ([kɛɪlʒ], [kreɪlʒ], [kreɪls], [kreɪls]). These stimuli spanned a continuum of wordhood violability, ranging from fully phonotactically licit forms ([kɛɪlʒ]) to a combination of sounds that is impossible in English ([kreɪls]). The MMN is particularly well-suited to an investigation into the processing of pseudoword and nonword acceptability because it provides an index of automatic auditory discrimination. Previous research (cf. Näätänen et al., 2007 for a comprehensive review) has demonstrated modulation of the MMN to numerous linguistic irregularities, suggesting that the component reflects a comparison of incoming auditory input against stored language-specific representations at early stages of processing. The questions we ask in this investigation revolve around the automatic processing of phonotactic irregularities and the consequences of these irregularities on the morphological shape of the pseudoword, specifically (1) what makes one pseudoword more acceptable than another, (2) when does a pseudoword drift into nonword territory, and (3) is acceptance more attributable to the phonological or morphological shape of the item, or is it a combination of both factors? If it is indeed a combination, then what drives acceptability (or rejection)? Ultimately, to what extent does the native speakers’ abstract knowledge of the constraints on wordhood affect processing?

Before presenting the experiment and data, we will briefly discuss classification of pseudopseudoword and nonword constructions (Section 2) and neurophysiological data for the processing of such constructions (Section 3). In Section 4, we present our experimental

configurations and predictions. Sections 5 and 6 contain, respectively, our methodology and results of the independent comparisons. Sections 7 and 8 contain the difference-of-difference analyses and matched representation analyses.

2. Pseudowords, nonwords, and “letter soup”

In experimental paradigms, pseudowords and nonwords are typically compared to real words as control conditions in order to isolate specific components of language processing. In lexical decision tasks, the classic purpose of pseudoword and nonword constructions is to make the task meaningful and serve as foil items against which the processing of real words can be measured. Critically, however, these items are not entirely free of interpretive complications; in fact, their phonological and morphological shape can profoundly influence how they are perceived and processed, and examples² of these complications abound in the experimental literature.

In their seminal study on the effect of letter position on perception, Rumelhart and McClelland (1982) employed English-like pseudowords and nonwords stimuli. They defined pseudowords as “pronounceable nonwords” and nonwords as “unrelated letter strings” and “unpronounceable and orthographically irregular non-words” (1982, pp. 72–74; see Table 1 for examples).

Recall that, among other restrictions, phonotactic constraints govern the existence of what a word is (and can be). As discussed earlier, certain sequences of consonants can be restricted in a language: one such constraint in English is that an obstruent + nasal cluster (e.g. [pn]) is only allowable in syllable codas, not in the word-initial position³; yet, note that *pnew* and *pnow* appear in Rumelhart and McClelland’s “pseudoword” (“pronounceable”) category. See also *posr* and *pasr*: this final [sr] cluster violates phonotactic rules (specifically sonority sequencing) of English.⁴ In the “unpronounceable” nonword category, we find *imla*, *ipra*, *olko*, *otko*, *ipna*, all phonotactically well-formed.

This discontinuity in categorisation persists across the experimental landscape. As mentioned in Section 1

Table 1. Example “pseudoword” and “nonword” stimuli (Rumelhart & McClelland, 1982).

Pseudowords			
deet keet	masp misp	nore nove	jain jair
fous vous	mosp musp	pnew pnow	sich sice
loob toob	posr pasr	sife sike	sool sook
Nonwords			
crea trea	olko otko	ahre ahte	oclo ocko
dmea kmea	rdka rpka	crhi crei	oplo opro
efte lfte	rldo rldo	imla ipra	rmka rmya

above, Stark and McClelland's (2000) pseudoword stimuli (used in a repetition priming study) become real words when pronounced aloud: *hart*, *tike*, *lare*, *hich*, *cort*, *rold*, *dold*. Their nonwords, on the other hand, are entirely "letter-soup", made up of strings of consonants: *bdxj*, *jfgp*, *kbqd*, *xvjd*. In De Soto and De Soto (1985)'s picture-word interference task, nonwords were employed in which "all vowels were replaced by consonants that are visually confusable" (p. 120); however, alongside the anticipated "letter soup" combinations such as *gzrtz*, *smlb*, *brct*, *httcp*, we find the perfectly pronounceable *porg*. Additionally, variation occurs not only in the phonological shape of nonwords, but also in what could be perceived as morphological: in a speeded pronunciation task, McCann and Besner (1987) used nonword controls such as *croop*, *jinje*, *coalp*, *lonss* as well as *snocks*, *phecks*, and *luks* – forms that would arguably invoke plurality due to the word final (see Apel & Lawrence, 2011, for a discussion of morphological awareness and orthography).

While it could be argued that these stimuli sets were developed decades ago, many of these lists remain in active use. Rumelhart and McClelland's stimuli have been used in numerous studies, including Chase and Tallal (1990) who used the sets to investigate the role of context in letter identification in adults and children with dyslexia. McCann and Besner's stimuli have been used by Simos et al. (2002) to investigate brain areas involved with reading words, Harm and Seidenberg (2004) to investigate the relationship between orthography and phonology in reading, and Gasper et al. (2025) for a study on affective responses and neutrality. Consequently, early classification decisions continue to shape current experimental practice, and when these stimuli often vary in their degree of lexicality, phonotactic probability, and morphological plausibility, these factors may affect both behavioural and neural responses.

3. Pseudowords and nonwords in the brain

3.1. Lexicalisation

Traditionally, the assumption has been that the more a stimulus resembles a real word, the more linguistic processing it will recruit: thus, **toble* may activate a lexical search and partial activation of representations related to *table*, while ***xqrtl* will be rejected before any substantial linguistic processing occurs. Under this framework, pseudowords are generally considered to engage many of the same mechanisms as real words since they conform to the phonological and/or orthographic constraints of the language. However,

behavioural and neurocognitive data suggests that the picture is considerably more complicated.

Laxon et al. (1988) compared children's ability to pronounce "friendly" nonwords (i.e. nonwords that had similar orthographic shapes to real words such as *flad* < *glad*, *flat*, *fled*) to "unfriendly" nonwords (e.g. *blid*, which they argued had "few" neighbours): they found that the "friendly" items resulted in significantly fewer errors in production. Connine et al. (1993) found that nonwords differing in a single linguistic feature in word onset from a base word (e.g. **zuffer* from *suffer*) resulted in significant semantic priming while those that deviated by more than two linguistic features (e.g. **nuffer* or **fuffer*) did not.⁵ Using fMRI, Raettig and Kotz (2008) examined the visual processing of pseudowords that were either phonotactically legal and transparently derived from real German words (e.g. **Elefunt*, **Elufant* for *Elefant*, "elephant"), phonotactically legal and opaque (**Dradofent*), or phonotactically illegal and opaque (***Dkdofent*). Pseudowords elicited greater bilateral superior temporal activation than real words, while derivationally transparent pseudowords were distinguished from opaque pseudowords in the left inferior parietal lobule: importantly, this latter effect reflected weaker deactivation for transparent forms. In contrast, phonotactic legality alone did not produce a significant difference, suggesting that different sublexical properties do not necessarily contribute equally to the neural processing of novel forms. However, the authors cautioned that the phonotactic violations (invoked by "making the first syllable of all opaque pseudo-words an illegal CC cluster, e.g. *dk*", cf. p. 422) may not have been sufficiently salient and may have undergone perceptual repair. At the very least, these findings suggest that linguistic processing is influenced by multiple dimensions, such as phonotactic probability, orthographic legality (for visual processing), neighbourhood density, morphological structure, and semantic plausibility.

EEG research (cf. Ziegler et al., 1997; Friedrich et al., 2006; Novak, 2006; Otten et al., 2007; Strand et al., 2008; Juphard et al., 2011; Bermúdez-Margaretto et al., 2018; Mattheiss et al., 2018; Matas et al., 2021; see also Martínez-Tomás et al., 2025 for a comprehensive review) has also shown evidence that pseudowords and nonwords are processed differently. Ziegler et al. (1997) recorded ERPs for two letter-search tasks and a semantic categorisation task using stimuli that consisted of visually-presented real French words, pseudowords (i.e. pronounceable letter strings that differed from real words by one letter and obeyed French orthotactic/phonotactic rules), and nonwords (orthographically illegal, unpronounceable letter strings). Across all three tasks,

responses for nonwords patterned differently from pseudowords and words, with pseudowords behaving more like real words. In the letter search tasks, a negative component (likely the N400, a component associated with semantic processing) was larger for words and pseudowords than for nonwords. There was also a weak LPC effect (the late positivity component, associated with recognition and memory) that was larger for nonwords than for words or pseudowords.

Coch and Mitra (2010) also found differences between ERPs for English pseudowords (e.g. **mard* or **nust*), nonwords (e.g. **zxqle*), and real words: pseudowords also resulted in a larger N300 effect (a negative-going component traditionally associated with representative exemplars) than nonwords. This finding, they argued, could be related to the pronounceability of the pseudoword stimuli in comparison to the nonword stimuli. Lastly, a larger N400 was elicited for words and pseudowords compared to nonwords, indicating a lexical-level effect (as opposed to earlier components, which reflect sub-lexical processing).

Carreiras et al. (2007) investigated transposed-letter (TL) similarity effects using event-related potentials (ERPs) combined with lexical decision to test whether consonants and vowels are processed differently during visual word recognition. They found that pseudowords containing two transposed letters (e.g. **jugde*) elicited reduced N400 amplitudes compared to nonwords in which those letters were replaced (e.g. **jupse*). Braun et al. (2009) created “pronounceable” German pseudowords by altering one, two or three letters of real words, resulting in a scale upon which the pseudowords ranged from “most word unlike” (e.g. **Knbe*) to “most wordlike” (e.g. **Kand*). N400 amplitudes for the three pseudoword types revealed a gradient effect: with the “most wordlike” types resulting in the largest negative ERP amplitudes (see also Holcomb et al., 2002).

3.2. Automatic processing

There is evidence that earlier ERP components (which are considered to reflect more attentionally and perceptually driven stages of processing) also respond to variations in the degree of “wordhood”. In a visual word processing study, Proverbio and Adorni (2008) distinguished between two types of pseudoword stimuli: (1) orthographically illegal strings, which violated Italian orthographic rules (e.g. unusual letter combinations, not pronounceable) and (2) orthographically legal pseudowords (pronounceable words). They found that orthographically illegal strings were rejected very early, showing effects around 170 ms, reflecting pre-lexical visual-orthographic analysis. Coch and Mitra (2010)

also found that pseudowords generated larger N1 amplitudes compared to nonwords (but this effect was smaller than for real words), and nonwords resulted in a larger P150 effect than both words and pseudowords, an effect the authors attribute to early difficulty in orthographic discrimination. Mitterer and Blomert (2003) found that Dutch pseudo-compounds (e.g. **tuimbank*) elicited asymmetrical responses in comparison to real compounds (e.g. *tuinbank*, “garden bench”) roughly 150 ms after presentation – but this asymmetry varied depending on the shape of the pseudoword, i.e. the degree of “viability” of the pseudoword (967).

This effect, the mismatch negativity response (MMN, Näätänen et al., 1978; Näätänen et al., 1992), is a negative-going component of event-related brain activity which usually peaks at around 100–250 ms after the onset of a deviant stimulus. In the classic MMN paradigm, identical, standard stimuli (similar to the form of a short-term memory trace) are presented repeatedly before the deviant, with the greatest distribution at frontocentral sites. The MMN is elicited when a less-frequently presented deviant mismatches to this representation, reflecting the degree to which the neural representation of the standard stimulus has been fixed. In the context of language, phonotactic constraints in standards and deviants play a crucial role in eliciting the mismatch negativity (MMN) response. When processing linguistic stimuli, the brain uses standards to establish a regular pattern of sounds, i.e. create a representation (cf. Näätänen et al., 2007; Schild et al., 2012; Eulitz & Lahiri, 2004). Crucially, this response depends on the participant’s native lexicon as well as the shape of the standard representation (cf. Dehaene-Lambertz, 1997; Honbolygó et al., 2017; 2020; Kirmse et al., 2008; Leppanen & Lyytinen, 1997; et al., 2021; Näätänen, 2001; Näätänen et al., 1997; Pettigrew et al., 2004; Pulvermüller et al., 2001, 2004; Shtyrov et al., 2000; Shtyrov et al., 2008; Tsukada et al., 2024).

Prior research (Näätänen et al., 1997; Aaltonen et al., 1993; Čeponien et al., 2003) has shown that the MMN responds to auditory contrasts in speech sounds; however, this discrimination extends beyond simple acoustic changes. In Mitterer and Blomert’s (2003) findings, a pair containing a “viable” pseudoword (e.g. **tuimbank*, where [m] takes on the feature [LABIAL] from the following [b]) elicited weaker MMNs than a pair which contained an “unviable” pseudoword (**tuimstoel*), where there was no viable phonological assimilation possible. Whiting et al. (2013) investigated early processing of morphologically-complex words and pseudowords containing derivational (-er) and inflected (-s) endings. They found that morphologically-complex pseudowords (e.g. *boker*) resulted in a

diminished MMN response compared to real words (e.g. *baker*), but there was no effect on the responses to pseudowords containing an inflected [-s] (e.g. **bokes*), or to real words (*bakes*). This suggests that the MMN reflects automatic processing of acoustic and phonological information in pre-lexical processes of word recognition.

MMN responses reflect the extent to which a deviant violates the representation established by the standard. In this sense, MMN amplitude is entirely relational, depending on the **comparison** between the standard and the deviant, rather than the deviant alone. In linguistic paradigms, this comparison is therefore influenced by the linguistic status of **both** stimuli and studies employing pseudowords often result in directional asymmetry, with the magnitude of the MMN response depending on which form of the contrast serves as the standard and which serves as the deviant (cf. Steinberg et al., 2010; Ylinen et al., 2016; Kotzor et al., 2020; et al., 2021). Asymmetries have been attributed to underspecification, categorisation, frequency, and predictive coding accounts; what is clear, however, is that there is modulation in the degree to which novel auditory information can be integrated into existing phonological and morphological representations.

4. This study

To investigate how specific combinations of constraints contribute to the identification of a pseudoword's structure, we conducted an auditory oddball task designed to elicit the MMN. We employed four English-like stimuli items – [kreɪs], [kreɪz], [kreɪls], and [kreɪlz] – as both standards and deviants across an eight-block, two-session study. These stimuli were designed to cover a spectrum of legality in terms of what is a possible word in English; crucially, this legality was tied to both the phonological and morphological status of the pseudoword.

From a phonological perspective, there are several elements which make up a word: a sequence of phonemic segments, vowel and/or consonantal quantity, syllable structure, and foot structure. All four of our pseudowords contained the same initial consonant cluster [kr], followed by a difference in length of the medial vowel ([ɛ] vs. [eɪ]), and thus a difference in moraic length of $\mu/\mu\mu$, and alternation of the final consonant ([s] vs. [z]) following an [l]. Recall that a word's morphological structure also plays a role when determining wordhood. In English, there are constraints which govern whether a noun will likely be perceived as singular or plural, the most well-known example being the plural marker [z] as in the cluster [ndz] (*towns*, *clans*). This plural marker can be realised in three ways (i.e. as the three different allomorphs [s],

[z], [+z, əz]) depending on the word's final consonant environment, cf. [kæps] *caps*, [bɛlz] *bells*, [pɪsɪz] *pieces*. This sound can also occur at the end of a monomorphemic word, e.g. [branz] *bronze*, but this is constrained heavily by the phonotactic environment which precedes it.

Critically, pseudowords are not immune from these constraints: while it matters what a language's phonemes are (and which features are contrastive), the **combinations** of these features and phonemes are equally important when it comes to word (and nonword) recognition. Our predictions for the perceived acceptability of our four pseudo/nonword items are thus:

- (1) *krelz* [kreɪz] contains the medial vowel [ɛ] (and thus a monomoraic rhyme) plus a sonorant consonant followed by a voiced strident. Owing to this combination, we predict that this stimulus will be perceived as an acceptable pseudoword in all of the configurations in which it appears, as it contains the fewest number of constraints on English word shape.
- (2) *kreilz* [kreɪlz] contains a bimoraic rhyme ($\mu\mu$) with [l] + a voiced [z] as an ending, which, following structural rules, should constrain it to being perceived as a plural form (i.e. the plural of whatever a *kreil* is).
- (3) *krels* [kreɪls], with the combination of a monomoraic rhyme (μ) ending with a voiceless strident in [ls], will likely be perceived only as a monomorphemic form (similar to English *else*), as this combination of sounds is illegal in an inflected English word.
- (4) *kreils* [kreɪls] contains a bimoraic rhyme ($\mu\mu$) that ends with an [l] + a voiceless strident [s]; this combination is impossible in English. We predict that this form will be perceived as the worst in terms of acceptability, closest to a nonword.

Our predictions also rely on assumptions about asymmetries in MMN responses. The mismatch negativity component responds to the deviance of a stimulus: the more a form diverges from the established exemplar (i.e. the standard), the greater degree of negativity the deviant will elicit. The effect that one sound has on another is not always symmetric: in numerous MMN paradigms, configurations in which the standard and deviant are swapped (e.g. /sonnet/[*sommet] vs. /*sommet/[sonnet]) often show an asymmetry in the strength of the MMN response (cf. Cornell et al., 2013; Kotzor et al., 2020; et al., 2021; Roberts et al., 2014).

One account for these findings is the Featurally Underspecified Lexicon model (FUL, Lahiri & Reetz, 2010): according to this model, not all sound properties are fully specified in the lexicon. When repeated

standards activate underlying lexical representations stored in long-term memory, deviants are compared against these features on the basis of the phonological features from the acoustic signal. Asymmetric MMNs have been interpreted as reflecting differences in the mapping of the stimulus onto the underlying representation, which either matches, tolerates (“no mismatch”), or mismatches in features. If a native speaker is indeed sensitive to an abstract notion of wordhood, we would therefore expect to find mismatches which reflect not only phonotactic acceptability, but also how those combinations of sounds affect the morphological shape of pseudowords. Our predictions for the MMN are therefore configuration-dependent (i.e. whether *kreils* is heard as a deviant in the context of *krels*) rather than solely stimulus-dependent. Specifically, we predict that the magnitude and direction of the deviant-standard effect will depend on **the linguistic environment** established through repetition of the standard. Because the standard provides the reference representation against which the incoming deviant is evaluated, the same form is not necessarily expected to elicit an equivalent mismatch response across configurations. Instead, we predict that the MMN will reflect the relationship between the phonological and morphological representations afforded by the standard, and those afforded by the subsequent deviant.

5. Methods and materials

5.1. Participants

Nineteen participants⁶ (mean age = 22.4 years) recruited at the University of Oxford took part in the study. One participant was removed due to equipment problems. They were all monolingual southern native British English speakers. All participants had normal or corrected-to-normal vision and self-reported as right-handed (a modified version of the Edinburgh Handedness Inventory was also used to confirm handedness, cf. Oldfield, 1971). No history of neurological disorders or hearing deficits was reported. The experiment was approved by the Central University Research Ethics Committee (CUREC) and written informed consent was obtained from all participants prior to the experiment. Participants were compensated appropriately for their participation.

Although the final sample comprised eighteen participants, the design provided a high number of observations, with eight blocks of 700 trials each (total number of trials per participant = 5600). This density of repeated auditory presentations is well suited to MMN paradigms, where component estimation depends

heavily on the stability of averaged responses across trials. Thus, while the sample size was modest, the large number of trials per participant increased within-subject reliability and provided sufficient power to detect robust automatic discrimination effects.

5.2. Stimuli, paradigm, and procedure

Multiple repetitions of the stimuli were recorded by a female native speaker of Southern British English in a sound-attenuated recording room using a professional quality USB microphone (Røde NT-USB) at a sampling rate of 44.1 kHz and in mono channel. The words were presented in a list of unrelated words in a randomised order. The speaker provided eight tokens of each word, and we extracted and manipulated the stimuli using the speech analysis software Praat (Boersma & Weenink, 2020).

As the aim was to keep the acoustic differences between the stimuli in each comparison minimal, we cut four tokens of each “stem” (i.e. [krɛl]/[kreɪl]) from the original recording and cross-spliced four tokens of the final consonants [s] and [z] from the original recordings to ensure they were identical across all stimuli. We then adjusted the duration of the vowel by cutting individual, non-consecutive glottal pulses (see Figure 1 below). All stimuli were maximally matched for their acoustic properties in all conditions and normalised to have the same peak sound energy. The intensity of all stimuli was also equalised to 75 dB using Praat.

The study was constructed using a standard oddball paradigm with a standard-to-deviant ratio of 85% / 15%, with ten consecutive standard stimuli occurred at the beginning of each block. Each of the four stimuli was used once as a standard and once as a deviant. As a result of this design, eight blocks were presented to each participant, with the order of blocks counterbalanced across participants (see Table 2).

Within each block, the deviant occurred pseudo-randomly among standards with a probability of 15% with at least two standard stimuli between deviants. The ISI was 600 ms, and stimuli were pseudo-randomised. During each session, participants were seated in a sound-attenuated, shielded EEG booth at a comfortable distance from a screen. They first performed an electro-oculogram (EOG) calibration task before the start of the experimental task. During the main task, participants watched a nature documentary without sound while the stimuli were presented through headphones (Sennheiser PX200). The total duration of each session was approximately 90 min including setup; participants were given the option of short breaks after every block.

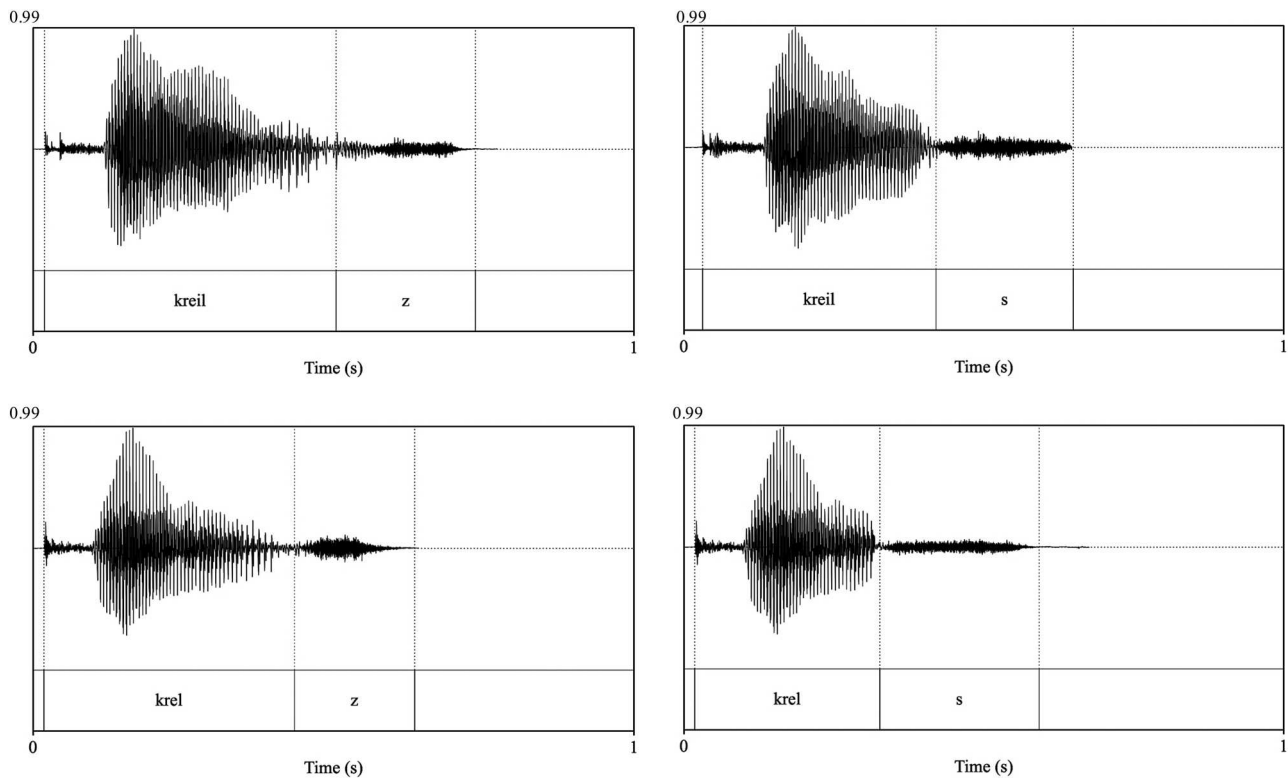


Figure 1. Oscillograms of the four stimuli.

5.3. Data acquisition

EEG recordings were made using a Biosemi ActiveTwo amplifier with 64 sintered Ag/AgCl pin electrodes placed in a 10-20 montage and online referenced to the mastoids. EOG activity was measured using four facial electrodes (IO1, IO2, LO1, LO2). All electrode offsets (in an active-electrode system this is comparable to impedance) were kept below 30 mV and signals were digitised at 2048Hz.

5.4. ERP analysis

EEG data were analysed offline using EEGLAB 14.1.2b (Delorme & Makeig, 2004), and ERPLAB (Lopez-Calderon & Luck, 2014). All continuous data was downsampled to 256 Hz and digitally filtered offline in the 0.3–30 Hz range using a Finite Impulse Response filter (FIR filter).

Bad channels and artefacts were detected and removed automatically with the Artefact Subspace Reconstruction (ASR) method as implemented in the Clean Raw Data plug-in. Data were subsequently re-referenced to the linked mastoids for all analyses except for mastoid amplitudes. By conducting an Independent Components Analysis (ICA, Makeig et al., 2004), ICA components that may represent eye blinking, lateral eye movement, muscle activity or channel noise were detected and excluded from further analysis. Epochs were created from –100 to 800 ms with the time window from –100 to 0 ms used as a baseline. An additional artefact detection was carried out to ensure that trials were rejected if they exceeded an amplitude of 100µV. Any participant with a trial-acceptance rate lower than 70% was excluded. The average number of epochs (and standard deviation) can be found in Table 3.

To ensure that ERP responses reflected processing of the critical phonological contrast rather than differences in stimulus onset, trigger markers were manually aligned to the onset of the phonological segment at which the stimuli diverged acoustically – this was done prior to any preprocessing. For each stimulus pair, the trigger was placed at the beginning of the critical sound, representing the earliest point at which the two forms could be distinguished (e.g. the onset of the vowel nucleus

Table 2. Block design for the experiment.

Block	Standard	Deviant
1	[kreɪls]	[kreɪlz]
2	[kreɪlz]	[kreɪls]
3	[krɛɪls]	[krɛɪlz]
4	[krɛɪlz]	[krɛɪls]
5	[krɛɪls]	[krɛɪls]
6	[kreɪls]	[kreɪls]
7	[kreɪlz]	[kreɪlz]
8	[kreɪlz]	[krɛɪlz]

Table 3. Average number of epochs (and standard deviation) for each condition .

<i>kreils ~ kreilz</i>		<i>krels ~ krelz</i>	
Standard	Deviant	Standard	Deviant
<i>kreils</i> : 565.7 (22.8)	<i>kreilz</i> : 100.3 (4.3)	<i>krels</i> : 572.4 (20.1)	<i>krelz</i> : 100.5 (4.7)
<i>kreilz</i> : 566.0 (20.3)	<i>kreils</i> : 99.4 (4.0)	<i>krelz</i> : 571.3 (20.5)	<i>krels</i> : 101.4 (3.4)
<i>kreils ~ krels</i>		<i>kreilz ~ krelz</i>	
Standard	Deviant	Standard	Deviant
<i>kreils</i> : 566.18 (25.3)	<i>krels</i> : 99.6 (4.7)	<i>kreilz</i> : 570.8 (20.2)	<i>krelz</i> : 99.6 (5.3)
<i>krels</i> : 568 (26.5)	<i>kreils</i> : 99.3 (6.0)	<i>krelz</i> : 566.12 (23.9)	<i>kreilz</i> : 100.2 (6.9)

constituting the critical phonological contrast in [krels]/[kreils]). The mean amplitude of the MMN was determined using the ERPLAB Toolbox (Lopez-Calderon & Luck, 2014). Based on visual inspection of the grand-average waveform, the mean peak amplitude of MMN (Tables 4–7) was determined for each participant and condition as the peak amplitude within 150–300 ms after the trigger at Fz.

We ran two-tailed nonparametric permutation tests for each configuration based on the *t*_{max} statistics (Blair & Karniski, 1993) using the Mass Univariate ERP Toolbox (Groppe et al., 2011). This data-driven approach was applied on account of our novel experimental manipulation and the manual shifting of our triggers, both of which could have a possible impact on the MMN time-window and/or topographical distribution of the effect. In a nutshell, with this statistical approach, time-windows and electrodes do not need to be specified a priori as for conventional ANOVAs. Rather, the univariate tests compare participants' ERP amplitudes in different conditions (i.e. standard vs deviant);

Table 4. Mean amplitude of MMN peak at Fz in window 150–350 ms for all conditions.

Mean peak amplitude (μV)		
standard	<i>kreils</i> : –2.71	<i>kreilz</i> : –1.54
deviant	<i>kreilz</i> : –1.72	<i>krels</i> : –3.46
difference	0.99	–1.92

Table 5. Mean amplitude of MMN peak at Fz in window 150–350 ms for all conditions.

Mean peak amplitude (μV)		
standard	<i>krels</i> : –2.66	<i>krelz</i> : –2.15
deviant	<i>krelz</i> : –3.69	<i>kreils</i> : –3.69
difference	–1.03	–1.54

Table 6. Mean amplitude of MMN peak at Fz in window 150–350 ms for all conditions.

Mean peak amplitude (μV)		
standard	<i>krels</i> : 0.62	<i>kreils</i> : –0.42
deviant	<i>kreils</i> : –0.56	<i>krels</i> : –0.56
difference	–1.18	–0.56

Table 7. Mean amplitude of MMN peak at Fz in window 150–350 ms for all conditions.

Mean peak amplitude (μV)		
standard	<i>krelz</i> : 0.25	<i>kreilz</i> : 0.65
deviant	<i>kreilz</i> : –0.17	<i>krelz</i> : –0.64
difference	–0.42	–1.29

this is performed for each channel across all time-points that are specified. We ran separate tests comparing the standard and deviant items in each configuration (e.g. *kreils* – *krels*, *krels* – *kreils*) by participant (Section 6), as well as post-hoc tests comparing matched deviants minus standards (e.g. *kreils* – *kreils*, see Section 7).⁷

To reduce the number of permutation tests, we specified both channels and time-points in a way that was broader than conventional MMN analyses where time-windows are chosen based on visual inspection, while at the same time being within a range of possible variations found across MMN studies. For the MMN analysis, we included time-points within 150–350 ms after the onset of the critical sound; given a sampling rate of 256 Hz, this resulted in one time-point for each 4 ms. As in previous MMN experiments, only fronto-anterior channels were included in the analyses: *AF3*, *F3*, *FC3*, *C3*, *AFz*, *Fz*, *FCz*, *Cz*, *AF4*, *F4*, *FC4*, *C4*.

Taken together, the permutation tests involved 12 electrodes x 53 time-bins, adding up to 636 comparisons which we conducted with a family-wise alpha level of .05. We set the random within-participant permutations to 2500 to estimate the distribution of the null hypothesis (i.e. no difference between conditions). Based on this estimate, critical *t*-scores were derived for each of our eight comparisons. More specifically, the most extreme *t*-value (the *t*_{max}) in each of the 2500 permutations was used to estimate our *t*_{max} distribution of the null hypothesis against which the 636 observed *t*-values were compared, i.e. one for each of our comparisons. This approach provides a strong control of the family-wise error rate and thus reliably locates effects in both space (electrodes) and time (time-points) (cf. Groppe et al., 2011). Please note, only clusters that survived cluster-mass permutation correction and extended across four or more consecutive time points (20 ms or longer) were considered significant and are reported here, as shorter clusters are more likely to be attributed to random noise than an effect (cf. Hayasaka & Nichols, 2003; 2004).

6. Results

The data, analysis code, and materials to reproduce the analyses and figures are available on OSF https://osf.io/whxd9/?view_only=13c3c8f017ca417db0594533553b0b85.

6.1. *Kreils* ~ *kreilz*

This configuration examined the relationship between the pseudowords *kreils* and *kreilz*.

- *kreils* [kreils] contains a bimoraic rhyme ($\mu\mu$) that ends with an [l] + a voiceless strident [s]; this combination is impossible in English.
- *kreilz* [kreilz] contains a bimoraic rhyme ($\mu\mu$) with [l] + a voiced [z] as an ending, thus constraining it to being perceived as a plural pseudoword.

Two separate analyses were performed: (i.) *kreilz* as standard, (ii.) and *kreils* as standard. Starting with (i.), 2500 random within-participant permutations of the data were used to estimate the distribution of the null hypothesis (i.e. no difference between conditions). Based on this estimate, critical t -scores of ± 3.1262 ($df = 17$) were derived; thus any differences in the data that exceeded this t -score were deemed reliable. The analyses showed stronger negativity for the deviant *kreils* lasting throughout the MMN time-window (i.e. 150–350 ms) which was distributed across all 12 electrodes (test-wise $\alpha = 0.006013$). For (ii.), the analyses showed stronger negativity for the standard *kreils* (and thus an overall effect of positivity in the difference wave) with a slightly more right-lateralised distribution across AF3, F3, AFz, Fz, FCz, Cz, AF4, F4, and FC4 (critical

t value = ± 3.7639 , $df = 17$, test-wise $\alpha = 0.002081$). Taken together, the results show a pattern of asymmetric activation, with *kreils* as a deviant in the context of *kreilz* eliciting greater MMNs than in the reverse condition (see Figure 2). In fact, in the reverse condition, *kreils* as a standard generated greater negativity than the accompanying deviant *kreilz*.

6.2. *Krels* ~ *krelz*

This configuration examined the relationship between our test items *krels* and *krelz*.

- *krels* [krels] contains a monomoraic rhyme (μ) ending with a voiceless strident, constraining it to a monomorphemic shape only.
- *krelz* [krelz] contains [ε] (and thus a monomoraic rhyme) followed by a sonorant consonant + voiced strident: thus, it could be perceived as singular or plural pseudowords.

Two separate analyses were performed: (i.) *krelz* as standard and (ii.) *krels* as standard. Starting with (i.), critical t -scores of ± 3.3875 ($df = 17$) were derived. The analyses showed stronger negativity for the deviant *krels* peaking around 250 ms with a slightly more right-lateralised distribution (test-wise $\alpha = 0.000997$). For (ii.), the analyses showed no significant effect for the standard

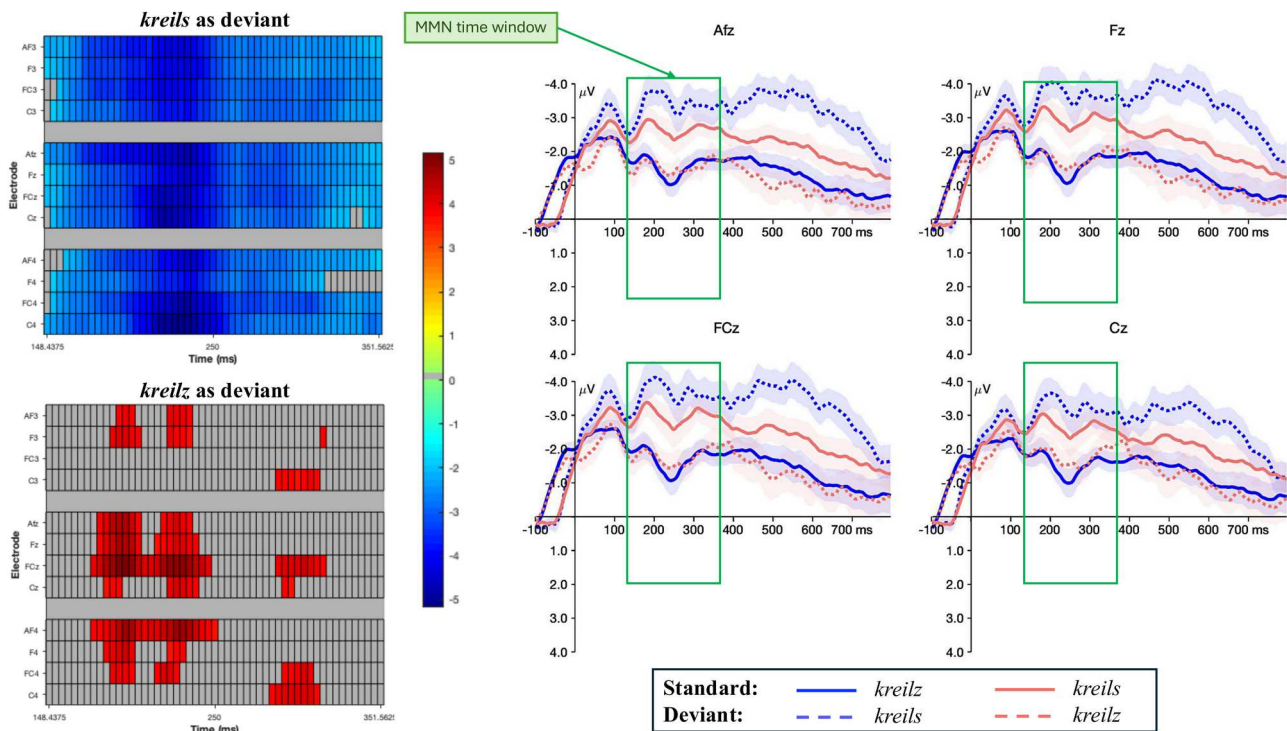


Figure 2. Mass permutation tests and individual waves for standard and deviant stimuli for *kreils* ~ *kreilz*. Note. negative waves are plotted up.

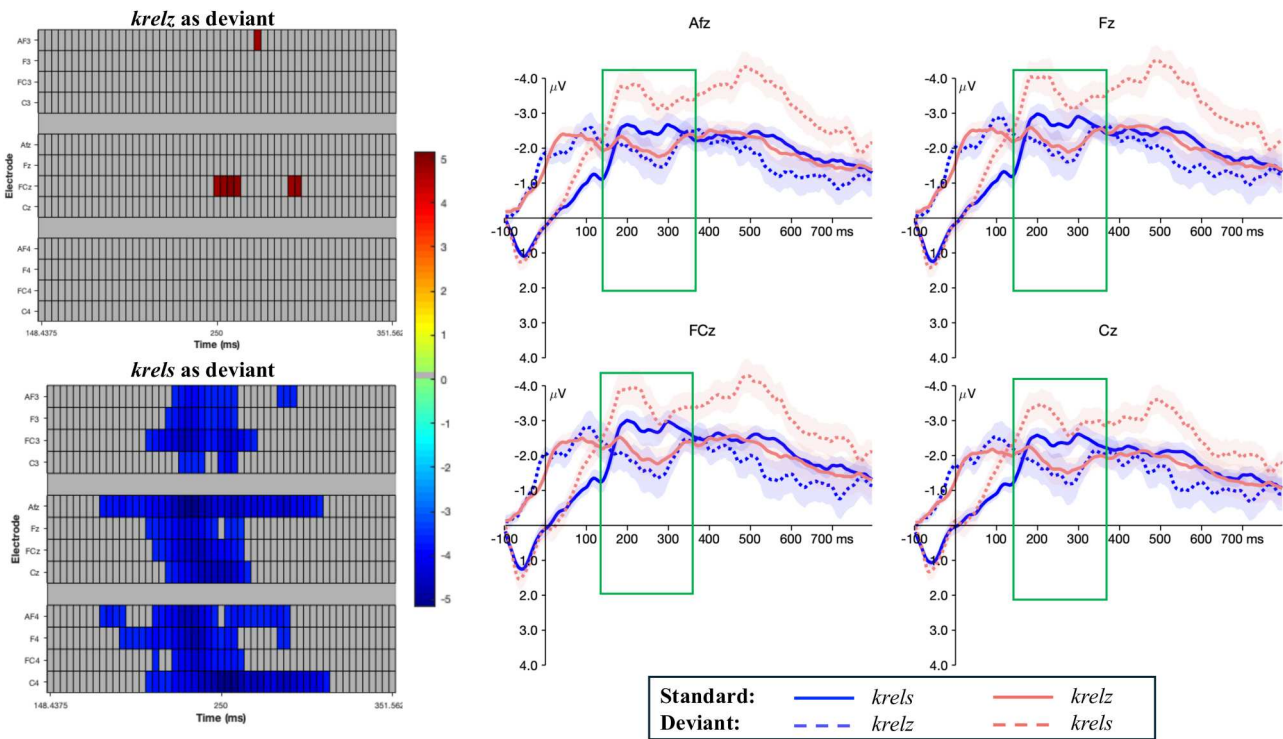


Figure 3. Mass permutation tests, and individual waves for standard and deviant stimuli for $krels \sim krelz$.

krels during the time-window (critical t value = ± 4.0404 , $df = 17$, test-wise $\alpha = 0.003369$). These results show a pattern of asymmetric activation, with the *krels* deviant in the context of the standard *krelz* eliciting significant negativity in comparison to the reverse condition, which did not exhibit any effect (Figure 3).

6.3. *Krels ~ kreils*

This configuration examined the relationship between our test items *krels* and *kreils*. Two separate analyses were performed: (i.) *krels* as standard and (ii.) *kreils* as standard. For (i.), critical t -scores of ± 3.9265 ($df = 17$) were derived. The analyses showed stronger negativity for the deviant *kreils* peaking around 200 ms, distributed across FC3, FC4, C3, C4, Fz, FCz, and Cz (test-wise $\alpha = 0.001056$). For (ii.), the analyses showed brief and limited negativity for *krels* as a deviant at the C4 electrode (critical t value = ± 3.9016 , $df = 17$, test-wise $\alpha = 0.001148$). In summary, the *kreils* deviant in the context of *krels* elicited a strong MMN while the reverse condition showed comparatively limited evidence of modulation (see Figure 4).

6.4. *Krelz ~ kreilz*

This configuration examined the relationship between our two test items *krelz* and *kreilz*.

Two separate analyses were performed: (i.) *krelz* as standard and (ii.) *kreilz* as standard. Starting with (i.), critical t -scores of ± 3.8274 ($df = 17$) were derived. The analyses showed only showed brief significant negativity for the deviant *kreilz* in relation to the standard *krelz*, and this was limited to the electrode C4 (test-wise $\alpha = 0.001352$). For (ii.), the analyses showed significant negativity for the *kreilz* deviant distributed across all 12 electrodes (critical t value = ± 3.8994 , $df = 17$, test-wise $\alpha = 0.001153$). To summarise, the results show a pattern of asymmetric activation, with the *krelz* deviant in the context of the standard *kreilz* eliciting an early, strong MMN effect while the reverse condition resulted in a comparatively weaker effect (see Figure 5).

7. Difference-of-differences analyses

For the difference waves, a deviant-minus-standard calculation was carried out for each participant and condition (see Appendix A). These analyses were conducted over the same 150–350 ms interval and electrode set as the primary (configuration-based) analyses. Again, only clusters that survived cluster-mass permutation correction and extended across four or more consecutive time points (20 ms or longer) were considered significant and reported.

In the *kreils ~ kreilz* condition, a robust difference between the *kreils* deviant and the *kreilz* deviant was

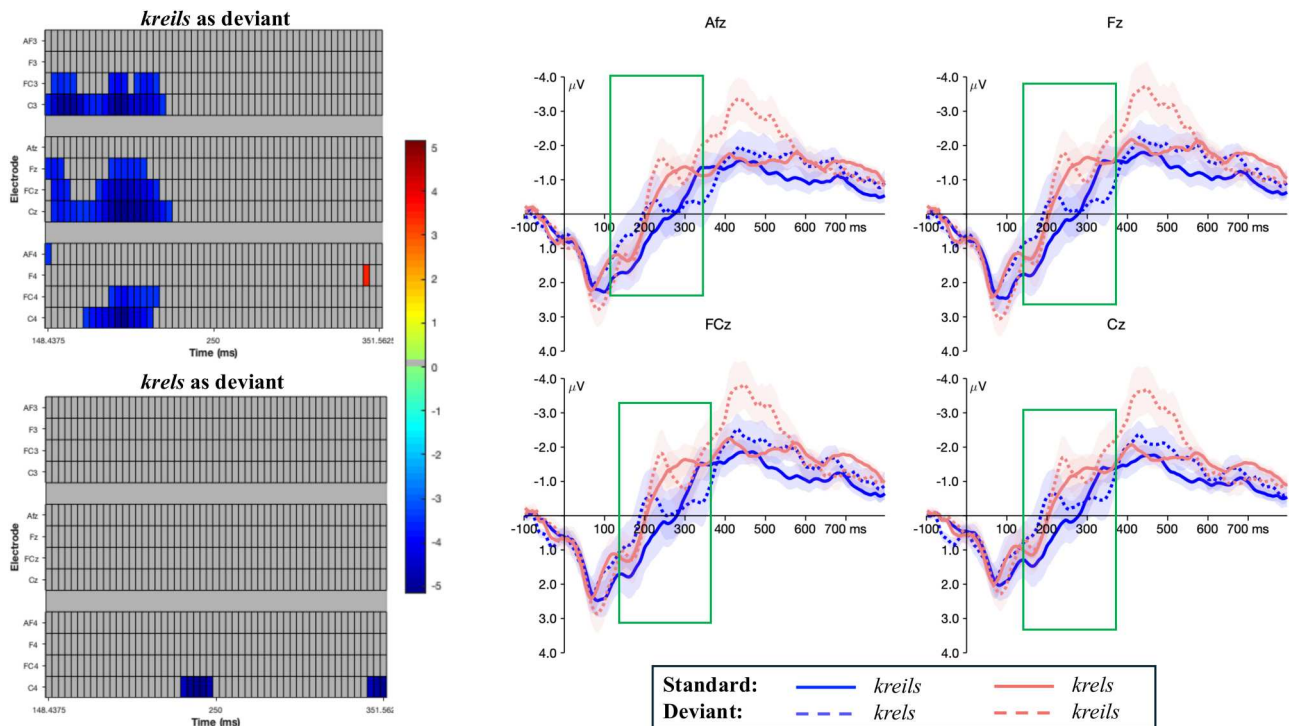


Figure 4. Mass permutation tests and individual waves for standard and deviant stimuli for *krels* ~ *krels*.

observed across the MMN time window. Critical t -scores of ± 3.165 ($df = 17$) were derived (test-wise $\alpha = .005658$). It remained broadly distributed throughout the remainder of the analysis window, persisting to approximately 350 ms (corrected $ps \leq .0492$).

In the *krels* ~ *krelz* condition, a robust difference was also elicited between the *krels* deviant and the *krelz* deviant from approximately 180–320 ms. Critical t -scores of ± 3.7478 ($df = 17$) were derived (test-wise $\alpha = .001756$). The effect emerged over frontal and

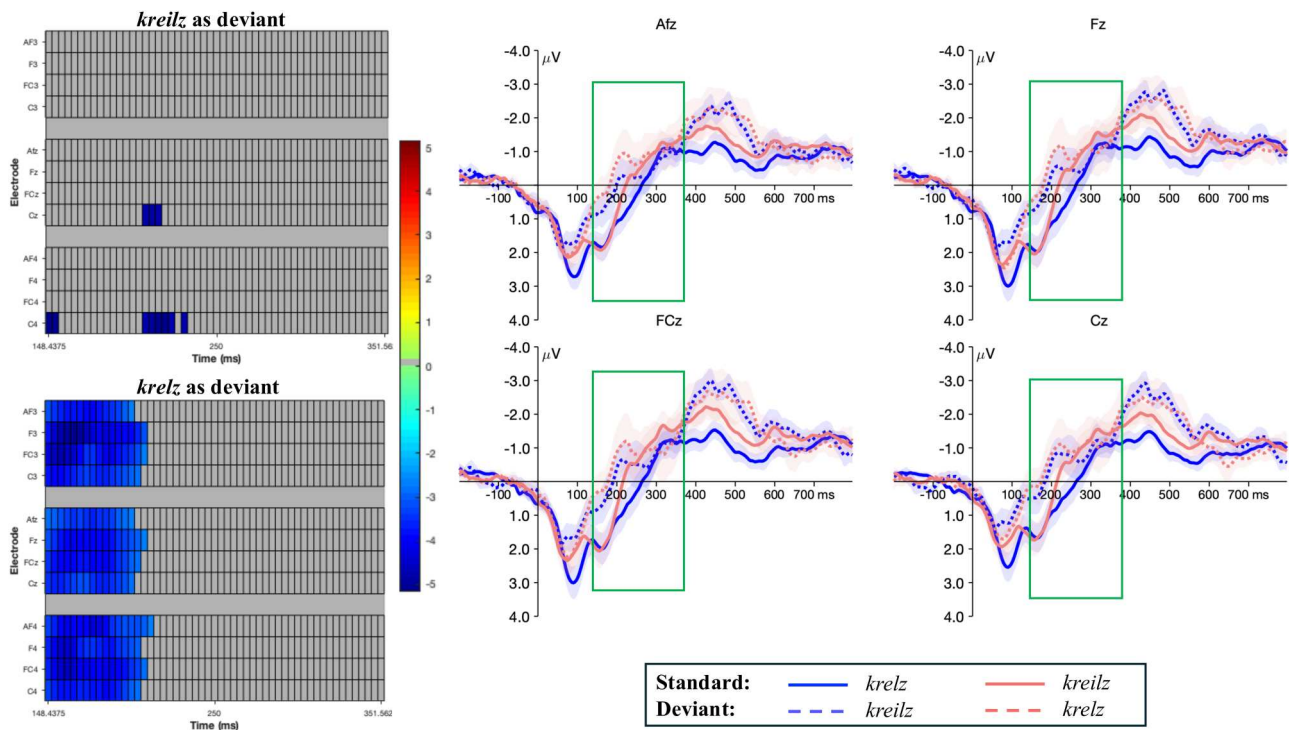


Figure 5. Mass permutation tests and individual waves for standard and deviant stimuli for *krelz* ~ *krelz*.

midline electrodes, rapidly spreading across most of the frontal-central electrodes by around 200 ms (corrected $ps = .0004\text{--}.0492$). In the *krels ~ kreils* comparison, the comparison between *krels* and *kreils* as deviant revealed a relatively late difference, emerging at approximately 330 ms. Critical t -scores of ± 3.9887 ($df = 17$) were derived, corresponding to a test-wise α of .000950. The effect initially emerged at C4 before spreading across predominantly frontal and right frontocentral electrodes between approximately 335 and 350 ms (corrected $ps \leq .0456$). No significant differences between the two deviant responses were observed during the earlier portion of the analysis window.

Lastly, although the two configurations showed markedly different patterns in the individual permutation tests, the difference between *krelz* and *kreilz* deviants was **not** supported by a direct difference-of-differences comparison: critical t -scores of ± 4.0849 ($df = 17$) were derived for the 150–350 window, corresponding to a test-wise α of .000772 and no electrode or time point reached significance following correction (all corrected $ps \geq .5216$). The apparent contrast between the significance maps in these difference-of-difference analyses therefore appears to reflect differences in the **strength and/or consistency** with which each effect differs from zero (and survives the family-wise correction), rather than a statistically reliable interaction between configuration and stimulus status. One additional method for investigating the source of these patterns is through analyses which compare the acoustically identical forms across their standard and deviant occurrences, i.e. matched deviant-standard.

8. Matched deviant-standard analyses

At a reviewer's suggestion, we ran additional post-hoc analyses comparing physically matched stimuli when presented as standards and deviants, e.g. *kreils* as a standard and *kreils* as a deviant in the *kreils ~ kreilz* configuration. These analyses were intended to determine whether the observed configuration-dependent patterns could be further characterised in terms of the behaviour of particular stimulus forms, rather than to provide confirmatory evidence for differences not supported by the direct configuration comparisons. Critically, these analyses did not reveal a uniform effect of standard minus deviant status (see Appendix B).

For *krels*, significant differences were observed in both configurations in which the representation occurred (i.e. *krels ~ kreils* / *krels ~ krelz*). In a comparison between *krels* as a deviant and *krels* as a standard in the *krels ~ kreils* configurations, critical t -scores of ± 3.6706 ($df = 17$) were derived (test-wise $\alpha = .001895$): a

significant difference between the two responses emerged from approximately 200–285 ms, with a broad frontal and central distribution. In a comparison between *krels* as a deviant and *krels* as a standard in the *krels ~ krelz* configurations, critical t -scores of ± 3.5624 ($df = 17$) were also derived (test-wise $\alpha = .002597$), with significant differences from approximately 150–190 ms. This suggests that this representation differed depending on whether it was heard as a standard or as a deviant in both configurations.

The *kreilz* item showed a brief spatially restricted deviant-standard difference when occurring in the *krelz ~ kreilz* configurations, lasting from approximately 150–155 ms; this was confined to five clusters in the centrally located electrodes Cz and C4 (critical $t = \pm 3.8129$, $df = 17$; test-wise $\alpha = .001391$). No significant difference was observed for this representation in the *kreils ~ kreilz* configurations (critical $t = \pm 3.8719$, $df = 17$; test-wise $\alpha = .001224$; corrected $ps \geq .4128$). Thus, *kreilz* showed only limited evidence of modulation by standard-deviant status. Descriptively, this suggests that the representation stayed relatively stable across its standard and deviant roles, with only role-dependent modulation appearing weak and specific to its pairing with *krelz*.

For *krelz* in the *krelz ~ kreilz* configurations, critical t -scores of ± 3.3914 ($df = 17$) were derived (test-wise $\alpha = .003472$), with a significant difference extending from approximately 150–225 ms across frontal and central electrodes. Conversely, no significant difference was observed for *krelz* as a deviant and *krelz* as a standard in the *krelz ~ krels* configurations (critical $t = \pm 3.5907$, $df = 16$; test-wise $\alpha = .002447$; corrected $ps \geq .6664$). Thus, this representation showed evidence for modulation when paired with the representation *kreilz*; when paired with *krels*, there was no difference.

Finally, neither matched comparison involving *kreils* was significant: no deviant-standard differences were found for this representation in any configuration, suggesting that this item was treated the same whether it was perceived as a standard or a deviant in any of the representational environments it appeared in. For *kreils* in the *krels ~ kreils* configuration, the critical t -scores for the deviant-standard difference were ± 3.7866 ($df = 17$; test-wise $\alpha = .001473$; corrected $ps \geq .0636$), while in the *kreils ~ kreilz* configurations, critical t -scores for the deviant-standard difference were ± 3.6349 ($df = 17$; test-wise $\alpha = .002048$; corrected $ps \geq .094$). Taken together, these patterns suggest that phonologically permissible forms may acquire different significance depending on the particular contrastive environment in which they occur. By contrast, sufficiently strong phonotactic violations (e.g. *kreils*)

may constrain this contextual flexibility, resulting in the comparatively stable response regardless of the form's local standard-deviant role.

9. Discussion

Across the theoretical and experimental linguistic landscape, there have been numerous discussions about what constitutes a pseudoword and/or a nonword. But something that is not possible can come in many shapes and sizes. As we saw in Section 2, some pseudowords are highly wordlike (**deet*), while others are only marginally pronounceable (**posr*). Likewise, “nonwords” can vary from minimally ill-formed (**pnaw*) to entirely “letter-soup” (***grftlhx*). This suggests that the distinction between pseudowords and nonwords is considerably less stable than traditionally assumed.

In particular, substantial variation is found in the phonological, phonotactic, and morphological properties of pseudowords and nonwords, leading to the possibility that these items occupy different positions along a continuum of linguistic acceptability (rather than representing clearly bounded categories). While findings already hint that phonology is certainly one of the key drivers of differences, what remains is a systematic investigation of how degrees of phonological well-formedness modulate processing, and how this affects perception of the morphological shape of the construction. Results from neurolinguistic studies have overwhelmingly indicated that pseudowords and nonwords elicit reliably different ERP responses (with pseudowords consistently patterning more like words). In addition to components associated with lexicalisation and higher-order categorisation or processing (e.g. N400, LPC), earlier ERP components traditionally associated with more automatic processing (N1, P150) have also been found to be sensitive to pseudoword and nonword structure (cf. Coch & Mitra, 2010; Proverbio & Adorni, 2008).

One such component, the mismatch negativity response (MMN), has shown sensitivity in particular to the degree to which a pseudoword violates the language-specific constraints of what constitutes a possible word. To probe the implicitness of such awareness, we turned to an oddball paradigm measuring the MMN in response to English pseudowords that contained different degrees of violability. We investigated two types of implicit constraints on “wordhood”: phonological and morphological. In terms of phonology, certain sequences of consonants are restricted by the phonotactics of the language; simply put, they can never occur together (cf. our nonword [kreils], which contained the impossible combination of [eɪ] followed by [ls]). There are also clusters of sounds that are allowable **only** in

monomorphemic words, but not in inflected or derived words. The reverse is also true, namely certain constraints are applicable only for monomorphemic words and not inflected (e.g. [bɛlz], not *[bɛls] for English *bells*).

Thus, there are effects attributable to phonological sequences, morphological structures, and the combination of the two that contribute to what constitutes a possible word in English. Our focus in this study was on what makes one pseudoword more acceptable than another; subsequently, in our predictions, we focused on how the interaction between phonological and morphological constraints might dictate automatic deviant minus standard discrimination. Following this, we expected differences in the strength of the MMN responses that reflect difficulties not only in establishing and accessing this representation, but also in matching the deviant stimulus to it. Our results were as follows.

Across the four stimuli, the pseudoword that resulted in the lowest indication of acceptability was – as predicted – *kreils* [kreɪls]. In the *kreils* ~ *kreilz* comparison, the *kreils* deviant elicited robust negativity across all electrodes in the MMN time window. In the reverse condition, the form also generated greater negativity as a standard than the accompanying deviant *kreilz* [kreɪlz]. Critically, this pattern is difficult to characterise solely in terms of the conventional standard-deviant relationship underlying the MMN (cf. Näätänen et al., 1997): with linguistic stimuli, the standard establishes a reference representation against which subsequent auditory input is evaluated, making the linguistic properties of both members of the contrast potentially important.

If novel forms differ not only in phonotactic well-formedness but also in their potential morphological structure, the resulting response may therefore **reflect sensitivity to multiple dimensions of linguistic organisation** rather than merely provide an index of phonotactic legality. Simply put, if we are unclear about what constitutes a pseudoword or a nonword, then we are also unclear about the nature of the representation being indexed by the MMN. The classic MMN account assumes that the repetition of a standard leads to formation of a memory trace against which an incoming deviant is subsequently evaluated. But what happens when the standard fails to fit any pre-existing exemplar? The effectiveness of a standard may critically depend on the extent to which it can be integrated into existing linguistic representations: thus, when a combination of sounds violates wordhood to such a degree, it becomes impossible to fix or build a standard representation.

We propose that this may account for the pattern observed for *kreils*. When *kreils* [kreɪls] served as the

standard, the phonologically permissible *kreilz* [kreilz] deviant elicited a less-negative response than the standard itself, reversing the pattern expected from a straightforward standard-deviant account. By contrast, when *kreils* occurred as the deviant and was evaluated against *kreilz* (a phonologically permissible English word form), it elicited the expected greater negativity relative to the standard. The same pattern was evident in the *krels* ~ *kreils* comparison, in which [kreilz] as a deviant in the context of the permissible standard *krels* [krels] elicited a stronger MMN effect than in the reverse configuration.

When *krels* [krels] occurred in a different contrastive environment, however, a different pattern emerged. In the *krels*~*kreilz* configurations, [krels] elicited an MMN when presented as a deviant against the standard [kreilz], whereas the reverse configuration produced no reliable standard-deviant difference. Importantly, although the matched-form analyses indicated that the response to *krels* was modulated by its standard-deviant role, the direction of the broader configuration effects was remarkably consistent: *krels* elicited the more negative response whether it occurred as the deviant or as the repeated standard. Thus, repetition and local oddball status modulated the response to the form, but did not eliminate its relative negativity compared with the accompanying representation. This suggests that *krels* remained a comparatively marked or weakly accommodated linguistic representation across contrastive environments, particularly compared to *kreilz*.

In the *kreilz* ~ *kreilz* comparison, we also found an asymmetry: *kreilz* as a deviant elicited a strong MMN effect while the reverse saw a much weaker effect. Although the difference-of-differences analysis indicated that the magnitude of the standard-deviant effects did not vary sufficiently consistently enough across participants to provide evidence for an interaction, the matched analyses, *kreilz* indicated that there was evidence for modulation when paired with *kreilz* (a representation that remained relatively stable across its other standard and deviant role, which was in the configuration with *kreils*). This finding was surprising, as we expected *kreilz* to be more generally accepted as a pseudoword form, even in comparison to *kreilz*. This pattern, however, is consistent with previous ERP asymmetries for durational contrasts (Cowan et al., 1993; Fritz et al., 2023; Fritz & Lahiri, 2025; Kirmse et al., 2008; et al., 2021; Mugitani et al., 2009; Tomaschek et al., 2013; Ylinen et al., 2006) and with phonological accounts (Hyman, 1985; Kenstowicz and Kisseberth, 1979; McCarthy, 1983) in which longer moraic structures incorporate their shorter counterparts, but not vice versa. On

such an account, *kreilz* is structurally contained within *kreilz*, potentially producing an asymmetry despite the greater pseudoword-likeness of *kreilz*; the absence of a comparable pattern for *krels* ~ *kreils* may reflect the overriding phonotactic ill-formedness of *kreils*, which effectively obscured this durational asymmetry.

Critically, the directional effects observed in the primary analyses did not appear to be reducible to a general tendency for particular forms to elicit greater negativity when presented as deviants. Rather, the combined pattern is consistent with the possibility that the neural response reflects not only mismatch to a local standard but also the degree to which a novel auditory form can be integrated into existing phonological and morphological representations.

These results suggest that “wordhood” is not a dualistic, categorical distinction. Novel phoneme sequences vary in the extent to which they conform to the constraints of English, and this variation may in turn constrain the morphological representations available to listeners. Experimental studies have classically operationalised this distinction in terms of phonotactic acceptability, with pseudowords treated as “possible” words and nonwords as “impossible” ones. Our findings instead point to a more graded representational landscape: although highly improbable or illegal sound sequences may elicit particularly robust mismatch responses (cf. [kreils] vs. [krels]), listeners appear sensitive not simply to the probability of individual phoneme combinations, but to the linguistic structures that those combinations make available.

In the present stimuli, this included whether a novel auditory form could support a monomorphemic representation, a morphologically complex representation, or potentially both. Therefore, what makes a novel form more or less “word-like” may depend not only on whether its constituent sounds are permissible, but on what those sounds allow the listener to represent. Critically, this also depends on the accompanying forms: in our configurations, it became clear that repetition could establish a statistical standard, but that did not necessarily make all standards linguistically equivalent. The absence of a consistent deviant minus standard effect across forms argues against a simple account in which these items elicit a uniform mismatch response when presented as deviant: instead, some representations show reliable modulation by stimulus status, whereas others show effects that vary according to the representation with which they are paired.

Thus, the linguistic well-formedness of the standard may constrain the reference representation against which subsequent input is evaluated: with the possibility

that phonologically permissible forms acquire different significance according to their contrastive environment, whereas sufficiently severe violations are less amenable to such contextual modulation. This is consistent with a graded processing account of nonword and pseudoword representations, in which the neural response reflects both the properties of the form itself and its relationship to the expectations established by the surrounding context.

10. Conclusion and further directions

Our findings highlight the importance of carefully evaluating the linguistic properties of experimental stimuli, even when designing foil items that will eventually be discarded in an analysis. Combining random sequences of phonemes (e.g. **iktros*) or altering a single phoneme in a real word (**pros* from *prop*) can indeed produce pseudowords; however, classifications based solely on phonotactic legality may overlook morphological cues that shape listeners' interpretation of novel forms and, consequently, their neural responses. In Näätänen's original (1978) MMN paradigm, the assumption was that the standard stimulus builds a representation: thus, if an established representation already exists, the corresponding deviant will either mismatch it or match it to varying degrees. On this basis, we assume that when a sequence of segments forms an impossible structure (such as [kreils]), native speakers cannot form a stable mental representation of it. This is precisely what we observed in our results: this structure was entirely incompatible with native English speakers' sense of wordhood.

Some caveats remain: all languages impose clear formal constraints on what counts as a possible word. In our study, we considered only a small subset of the constraints governing English monosyllabic words. Many others exist: for example, English does not allow an underlying bimoraic vowel followed by [ŋk] (**μμ[ŋk]*) in monomorphemic forms. Words such as *sink*, *tank*, and *punk* are well-formed, but sequences like [pi:ŋk] or [teɪŋk] are entirely unacceptable. However, when the final cluster is [nt], the bimoraic restriction no longer applies, as seen in *paint* [peɪnt] and *mount* [maʊnt]. The awareness of these violations underlies a notion of wordhood that may be understood as a component of native speaker **cognisance**: the internalised knowledge of which structures and processes are permissible in one's language. If so, further research on the acceptability of phonological structures in monomorphemic words, as well as potential conflicts between native and non-native lexical patterns or structures, is warranted.

Notes

1. In our notation, pseudowords are marked with * and nonwords are marked with **.
2. A particular challenge is that many studies do not provide complete stimuli lists, making it difficult to assess the criteria used for classification or evaluate the linguistic characteristics of the items themselves. This lack of transparency limits the reproducibility of the experimental findings as well as the ability of subsequent research to evaluate the stimuli properties upon which theoretical claims are based.
3. While it is true that [pn-] renders orthographic forms like *pneuma* or *pneumatic* (borrowings from Greek), English speakers typically drop the initial [p] sound, rendering [nu:mætɪk].
4. Presumably, English speakers would usually insert a vowel here to avoid a final [sr] cluster, e.g. [pəʊ.sər].
5. This effect was similar for nonwords in which the manipulation occurred word-medially or word-finally, leading the authors to argue that the processes that map acoustic-phonetic information onto lexical representations are blind to the position of the altered phoneme. However, it is worth noting that the initial consonants in the study were typically one feature apart and they did not control for *match-mismatch* features.
6. Data collection for this study began prior to the COVID-19 pandemic but was suspended for approximately 11 months due to restrictions on in-person testing. As the study required participants to complete two consecutive testing sessions, it was not feasible to resume the interrupted protocol with participants who had completed only their first session before the suspension. Data collection was therefore restarted, with new participants completing the full experimental protocol. Across the initial and restarted phases of the study, more than 40 participants were recruited for EEG testing **across the lifetime of this study**; the sample reported here comprises the N = 19 who completed the required sessions following the restart.
7. These analyses were exploratory and were not part of the original analysis plan. Since our central question concerned how a deviant was processed relative to the representational environment established by the standard (that is, whether the response to a given nonword depended on the particular representation against which it occurred), our critical contrasts were between each representational configuration.

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