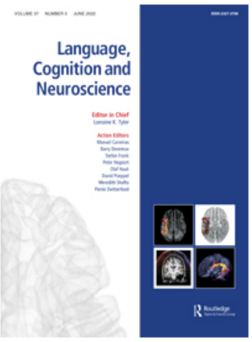

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Cognate status modulates the comprehension of isolated reduced forms

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ABSTRACT
There are competing theories about the representation of reduced variants of words in the mental lexicon. At the same time, speech reduction is known to cause problems for non-natives' speech comprehension. We investigate whether processing of full and reduced forms of cognates can help to better understand how reduced forms are represented in the mental lexicon. In an English auditory lexical decision task during which the brain response (EEG) was recorded, highly proficient Dutch learners of English listened to full and reduced forms of cognates and non-cognates. In the reduced forms, schwa was omitted. This schwa reduction occurred in either poststress or prestress position. While behavioural data (accuracy and reaction time) did not yield convincing information about the status of reduced forms, EEG data strongly suggest that form representations play an important role, in both prestress and poststress words. The results have clear implications for theories and models of spoken word recognition.

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1. Introduction

In spontaneous speech, words are often pronounced in a reduced form, with altered or fewer speech sounds and even with fewer syllables compared to the full citation form. For instance, the English words /'sʌməri/ (summary) and /'jɛstədeɪ/ (yesterday) may actually sound like /'sʌmri/ and /'jɛʃeɪ/. In a corpus of spontaneous conversations between American-English speakers, 25% of the content words are lacking a segment (Johnson, 2004). Reduction phenomena are also highly frequent in other Germanic languages, such as Dutch (e.g. Ernestus, 2000) and German (e.g. Kohler, 1990), and in non-Germanic languages such as French (e.g. Adda-Decker et al., 2005) and Finnish (Lennes et al., 2001). This variation raises deep questions about the representation of words in what is supposed to be the mental lexicon and about implications for conventional laboratory experiments that investigate the role of word representations in speech perception and production (e.g. Bürki & Gaskell, 2012; LoCasto & Connine, 2002). In this paper, we investigate the effects of reduction and cognate status on the global behavioural measures "accuracy" and "reaction time", after which we deploy more detailed analyses of EEG signals to uncover the time course of underlying cognitive processes in an attempt to shed light on the representations of reduced forms in non-native listeners.

In meaningful continuous speech, the details of the representation of words in the mental lexicon might not be crucial for speech comprehension, because additional resources such as top-down prediction and pragmatic (contextual) constraints help to understand the words. For example, the context provides crucial syntactic and semantic information that enables and supports word identification. Both the preceding and following contexts may help (van de Ven et al., 2012). Specific *syntactic* cues in speech processing by natives may help, as is shown in the eye-tracking study by Viebahn et al. (2015), which reports that Dutch native listeners recognised past participles more quickly if they occurred *after* their associated auxiliary verbs than when they preceded them. This order effect appeared stronger for casually than for carefully produced sentences.

The benefit of contextual cues in the processing of reduced speech suggests that native listeners hardly have problems in processing reduced speech that occurs in larger contexts. Mulder, ten Bosch, et al. (2018) showed that native Dutch listeners processed full and reduced forms of mid-sentence past participles

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in the same way. The assumption that speech reduction is not a problem in daily conversations is supported by the observation that native listeners are hardly aware of reductions in daily conversations.

Contextual clues are clearly absent during the processing of isolated word forms in laboratory experiments. Here, representational details are more relevant for speech comprehension. For stimuli presented in isolation, a processing advantage for full forms over reduced forms has been observed in native listeners' comprehension. One source of information that might help to overcome effects of reduction in processing isolated words could be the word's frequency. It is generally observed that words with a higher frequency of occurrence (often based on the corpus frequency of the written form) elicit shorter reaction times and fewer errors than words with a lower frequency (e.g. Brand & Ernestus, 2018; Murray & Forster, 2004; Ranbom & Connine, 2007). The relative frequency of full and reduced forms in normal conversations also plays a role, although that role might be complex. High-frequency words tend to be more reduced than less frequent words in conversational speech (e.g. Brand & Ernestus, 2018; Bybee, 1998; Connine et al., 2008; Jurafsky et al., 2000; Lindblom, 1990; Ranbom & Connine, 2007; Wright, 2004), suggesting an interaction between the roles of reduction and frequency. Activation-based models (e.g. Dijkstra & Van Heuven, 2002; Green, 1998; Marslen-Wilson, 1987; McClelland & Elman, 1986) of word processing predict that the number of errors and the reaction times depend on the match between a stimulus and a representation in the mental lexicon, as well as on some measure of the familiarity of the listener with a specific form.

Other research suggests that in isolated word processing, the activation of the meaning representations of reduced forms takes longer than activating the meaning representations of full forms. Van de Ven et al. (2011) conducted an implicit auditory priming experiment in which participants performed auditory lexical decision. The target words were preceded by prime words that were either reduced or full forms. Prime-target pairs differed in their semantic relatedness. If the targets were presented 1000 ms after the responses to the primes, only the primes that were full forms produced priming effects. If, in contrast, the targets were presented 1500–1600 ms after the responses to the primes, both full and reduced primes produced priming. These results suggest that reduced forms take longer than full forms to activate their semantic networks after they have been identified. In all, research on reduced form processing in isolation shows that processing seems to follow primarily a bottom-up up route, in which the activation of form information is the first hurdle to take. The strength of the form representation (i.e. possibly based on how frequent that form has been encountered) seems to determine how fast or successful word recognition proceeds. The result can then be delayed word recognition or word recognition may even fail completely.

Non-native listeners generally suffer more from reduction phenomena than natives. Both factors in activation-based models mentioned above are at stake: non-natives may have not encountered reduced forms as frequently as natives did (cf., Connine, 2004), and as a result, non-native listeners might have poorly-defined mental representations of reduced forms. Consequently, the processing of reduced forms will take more time and/or effort. Behavioural research on the processing of reduced speech has indeed shown that reaction times to reduced forms are slower than to full forms, and that the effect of reduction is larger in non-native listeners than in native listeners (e.g. Brand & Ernestus, 2018; Mulder et al., 2015).

Speech comprehension by non-natives might provide a window onto the representation of words in the mental lexicon. There is substantial evidence supporting the theory that second-language learners activate and access representations of words in both the native (L1) and second language (L2) in parallel. In addition, it is widely assumed that words of L1 and L2 are stored in an integrated lexicon (e.g. Dijkstra et al., 2010). This implies that the activation of words of the native language could influence the processing of full and reduced forms in the L2. At what level of word recognition this influence takes place is closely related to the question of how L2 reduced forms are represented and linked to L1 forms in the mental lexicon. One way to shed more light on this issue is to investigate how the *cognate* status of a word affects and modulates the processing of reduced forms.

When words share their meaning and largely overlap in form (spelling or pronunciation) between two languages, they are considered *cognates*. For instance, the English word cat /kæt/ and Dutch word kat /kɑt/ are translation equivalents that overlap in form. Behavioural and neurophysiological studies generally have shown faster and more accurate responses to cognates than to non-cognates in lexical decision tasks (see for an overview, Dijkstra et al., 2010). This is commonly taken as evidence that upon encountering a cognate, both language representations of this word are activated. The semantic and form overlap between the activated representations strengthens the activation of the input word, which leads to faster recognition.

However, this facilitatory effect is mostly found in visual word recognition, where the degree of form overlap is relatively easy to quantify. In the auditory domain, research on the effect of cognate status on isolated word comprehension is extremely scarce. Studies that aimed to show bilingual co-activation typically resorted to the use of inter-lingual homophones (words that overlap in phonology but have different meanings in both languages) or stimuli that overlap in word onset phonemes (e.g. Ju & Luce, 2004; Marian & Spivey, 2003; Schulpen et al., 2003; Weber & Cutler, 2004). These studies revealed co-activation based on phonological overlap between representations. For instance, Schulpen et al. (2003) observed slower response times for inter-lingual homophones compared to matched monolingual control words. These effects are similar in direction to the effects found in visual lexical decision for inter-lingual homographs (i.e. words that overlap in orthography, but not in meaning) and suggest that it is predominantly the meaning overlap between representations that determines the direction of the effects. A sufficient degree of form overlap, in turn, is a prerequisite for co-activation to occur. For instance, Dijkstra et al. (2010) observed a decrease in reaction time going from translation equivalents without any orthographic overlap to nearly-identical cognates, and even more facilitation for form-identical cognates. Combining the above-mentioned findings from visual and auditory word comprehension, we argue that cognate effects could affect auditory comprehension if there is enough form overlap, and that they should be facilitatory in nature, because the activated representations map onto the same semantic representation. In other words, co-activation could then help to overcome or weaken negative effects of reduction.

There are indications that cognate status and reduction indeed interact during word processing. Mulder et al. (2015) investigated the effects of cognate status in a behavioural study with highly proficient Dutch–English non-native listeners and a control group of English native listeners. In an English auditory lexical decision task, native and non-native participants listened to three-syllable Dutch–English cognates and English controls that were either presented in their full form or without their *poststress schwa* (e.g./'sʌmri/ for /'sʌməri/, summary). Both the reaction time and accuracy data reveal an overall inhibitory effect of reduction in both listener groups, and the effect of reduction was found to be equally large in both native and non-native listeners. Interestingly, the cognate status of a word did affect how listeners process reduced and full forms: Cognate facilitation was only observed in full forms (i.e. higher accuracy to cognates than to controls) and not in reduced forms, where the accuracy pattern is reversed and shows slightly lower accuracy for reduced cognates than for reduced controls. In addition, there was a larger negative effect of reduction in cognates than in controls. This suggests that in auditory lexical decision experiments cognate status and reduction interact in non-native speech comprehension.

1.1. Prestress vs. *poststress reductions*

In Mulder et al. (2015), the question was raised whether the interaction of cognate and reduction is unique to stimuli with a poststress reduced schwa, or whether it holds for words in general and thus also affects the processing of items with different reduction patterns. Reduction patterns depend heavily on the stress pattern of the words, since only syllables that are unstressed can be reduced. Because the position of word stress is supposed to be a cue for word segmentation in English (Cutler & Carter, 1987) and information in the word's beginning is highly relevant for how word processing evolves (Connine et al., 1993), it is interesting to investigate whether the effects of cognate and reduction is the same in polysyllabic words that have a weak first syllable (i.e. which can lead to prestress reduction).

Several studies investigated the lexical representation of English poststress and prestress schwa-reduced words in tasks using online methods in production (Bürki & Gaskell, 2012; LoCasto & Connine, 2002). These studies suggest that prestress schwa words have a single mental representation (with schwa present), while poststress schwa words have multiple mental representations (with and without schwa). Findings for the comprehension of poststress and prestress words are mixed and not always compatible with findings from production studies.

Patterson et al. (2003) examined a small number of two- and three-syllable pre- and poststress word types in the Switchboard corpus of conversational American-English telephone conversations (Godfrey et al., 1992). For high-frequency two- and three-syllable prestress words the schwa deletion rate was 15%, while 64.5% of three-syllable poststress word tokens showed deletions. The highest deletion rate for low-frequency prestress words was 12.7% (for tokens of morphologically complex three-syllable words), but 50.1% of three-syllable poststress tokens had the schwa deleted.

In order to obtain a better view of the stress patterns in English and Dutch, we consulted two dictionaries. The CMU Pronouncing Dictionary[1] – admittedly for American English – contains 112,072 word forms comprising two, three or four syllables. Of these, 77,100 (68.8%) have main stress on the first syllable and an unstressed (reducible) second syllable. The remaining two-, three- and four-syllable word forms have an unstressed (so, reducible) first syllable, and main stress on the second syllable. In the lexicon that comes with the Spoken Dutch Corpus (Oostdijk, 2000) there are 94,631 two-, three- or four-syllable words with unique pronunciation forms, 62,016 (65.5%) of which have main stress on the first syllable; 21,487 have main stress on the second syllable. Although the two dictionaries come from very different sources and therefore cannot be straightforwardly compared, it is still suggested that Dutch has the same proportion of "weak–strong"-initial words as (American) English. However, 7248 of the words with a weak first and strong second syllable have /bə/, /χə/ or /vər/ as their first syllable; these are highly frequent participle verb forms that are heavily reduced in most occurrences. Therefore, native speakers of Dutch are highly familiar with a "weak-strong" pattern in the first two syllables of a word.

The familiarity of native speakers of Dutch with schwa deletion in morphologically complex prestress words (van de Ven & Ernestus, 2018) raises the question whether this implies that morphologically simple prestress words might have double representations, similar to what has been suggested for poststress words. For cognate words this entails double representations for words of both languages. It is not clear whether Dutch L2 speakers of English would process prestress cognate words in a different way than poststress cognate words.

In sum, both the cognate status and position of reduction can provide a window into the representation of reduced forms. If the cognate status affects the processing of reduced forms, this could suggest that reduced forms have their own representation in the lexicon, as the effect of the co-activated L1 representations on the processing of the reduced target word can only occur if the representations are linked. However, whether and in what way cognate status affects reduced word processing is expected to depend on the position of the reduction. Therefore, the interactions between cognate status, reduction and position of the reduction will provide insights into whether and how reduced forms are represented.

In the present study, we combine behavioural and electrophysiological methods to investigate whether cognate status provides a window onto the representation of post- and prestress ə-reduced words. For that purpose, we use a lexical decision task with Dutch highly proficient learners of English. Accuracy and RT are behavioural measures that characterise some (important) aspects of the response of individual participants to individual stimuli. However, those behavioural responses are the cumulative result of several parallel and serial cognitive processes that take place during and after the unfolding of the acoustic stimuli, including phonetic form decoding, lexical-semantic access, bottom-up and top-down processing, and decision making. Therefore, behavioural measures cannot reveal the time course of the cognitive processes that generated the behaviours. As a consequence, accuracy and RTs provide only indirect information about underlying representations. For that reasons, we investigate whether analyses of EEG signals can uncover the time course of the cognitive processes involved in L2 lexical decision. Differences between EEG responses related to full and reduced cognates and corresponding control stimuli, could shed more light on the question whether the mental lexicon contains representations of reduced pronunciations.

1.2. The use of EEG to capture the time course of cognitive processes

There is a vast literature on the relation between EEG responses and cognitive processes. However, there are still many questions about the interpretations of experimental findings (e.g. Kutas & Federmeier, 2011). The EEG literature relates phonetic form processing of linguistic stimuli to early ERP components such as the N100, while it is assumed that lexical-semantic processing is reflected in the later N400 component (e.g. Swaab et al., 2012).

N100 effects have been specifically observed for the processing of word onsets. Behavioural and electrophysiological studies have shown that listeners selectively attend to word onsets in continuous speech and process these onsets at an early perceptual stage (e.g. Astheimer & Sanders, 2011; Connine et al., 1993; Marslen-Wilson & Zwitserlood, 1989; Salasoo & Pisoni, 1985; Sanders & Neville, 2003a, 2003b). One reason why some stimulus features receive more attention than others is that they are perceptually more salient or odd. For instance, Sanders and Neville (2003b) observed enhanced N100 in response to onsets that are more difficult to segment than to onsets that are easier to segment. In our lexical decision experiment, segmentation effects play no role since the participants processed words presented in isolation, but processes related to the *detection* of the onset of a stimulus are involved. In the reduced prestress stimuli there may be an additional effect that is known as the Phonological Mismatch Negativity (PMN) (Praamstra et al., 1994). Because isolated words tend to be spoken with their (full) citation form, the PMN might be invoked by reduced forms of words spoken in isolation.

The N400 is the most-studied ERP component associated with the processing of semantic information. It is assumed that the N400 effect reflects differences in the fit between the meaning of a word and its context (e.g. a word, sentence or larger speech unit), with a larger N400 associated with a less appropriate fit. Most research on the N400 has focused on sentence-final target words that cause some sort of semantic violation. For instance, Kutas and Hillyard (1984) showed that words that form a semantically anomalous ending to a sentence (e.g. *The pizza was too hot to cry*) elicit a larger N400 than sentence-final words that are semantically appropriate (e.g. *The pizza was too hot to eat*). For that reason, the amplitude of the N400 has been related to the difficulty of accessing lexical-semantic representations, with more negative N400s for words that require more effort to process.

The N400 component has also appeared to be sensitive to manipulations of words presented in isolation (see Kutas & Federmeier, 2011 for an overview of N400 research). For instance, more negative N400 amplitudes have been observed in response to short bisyllabic Spanish words that start with a high-frequency syllable in a visual lexical decision task (Barber et al., 2004). The authors suggest that the N400 amplitude is a function of the number of words that are activated. However, Mulder et al. (2013), also in a visual lexical decision task, found that words with a large morphological family size result in a less negative N400 amplitude. The authors attribute this to the fact that the activated morphological variants facilitate the recognition of the stimulus as a real word.

Cognate status is also known to affect N400s. Cognate effects in the form of less negative N400 amplitudes have been found by Yudes et al. (2010), Midgley et al. (2011) and Peeters et al. (2013). This suggests that the effect of cognate status is mainly semantic in nature (see for a discussion Costa et al., 2005; Mulder et al., 2014), as L2–L1 co-activation results in increased semantic activation. Finally, a larger N400 is also commonly observed for pseudowords relative to real words (e.g. Laszlo & Federmeier, 2009). This larger N400 amplitude for pseudowords is explained as an index of a failed lexical search process, because it takes more time and effort to search for forms that are not present in the lexicon. To sum up, a larger (i.e. more negative) N400 to words in one condition versus words in another can reflect both the number of word candidates that are activated and the difficulty of accessing lexical-semantic representations for these words and integrating them into a given context.

The above-mentioned studies discuss the *amplitude* of the N400 effect. However, van de Ven et al. (2011) suggest that *reduced* word forms take longer than full forms to activate their semantic networks after completion of phonetic decoding. As a result, an ERP component related to lexical-semantic access of reduced forms might be *delayed* relative to the corresponding component for full forms. In addition, the negative amplitude might be larger. Both the *latency* and *amplitude* effects were confirmed by Drijvers et al. (2016). Thus, lexical-semantic activation of reduced forms may proceed more slowly and require more effort compared to full forms. Two competing (but not necessarily mutually exclusive) explanations have been advanced. Ranbom and Connine (2007) and Brand and Ernestus (2018) hypothesise that it is because the representations of reduced forms are weaker, which may imply that reduced forms are represented in the mental lexicon. On the other hand, Kemps et al. (2004) and Brouwer et al. (2012) maintain that listeners may need to reconstruct the full form to access semantic representations, implying that the mental lexicon does not necessarily contain useful representations of all reduced forms.

The summary of findings in previous electrophysiological studies shows that information in EEG signals does not allow for straightforward interpretations in terms of cognitive processes and representations in the mental lexicon. Although effects that occur early in a word are conventionally related to form processing and later effects to lexical-semantic access, in actual fact these processes may at least in part overlap. Especially in auditory lexical decision experiments, where pseudowords may only deviate from real words towards the end of a stimulus, phonetic decoding may well continue until the end of the acoustic stimulus. At the same time, semantic effects can occur earlier in time (e.g. Dell'Acqua et al., 2010; Penolazzi et al., 2007; Segalowitz & Zheng, 2009). For example, it is difficult to explain the effect of word frequency in lexical decision experiments without assuming simultaneous bottom-up (phonetic decoding) and top-down (lexical-semantic access) processes (e.g. Dahan et al., 2001; Nenadić & Tucker, 2018; Norris & McQueen, 2008; ten Bosch et al., 2015). For these reasons, we decided not to focus on conventional ERP components, such as the N100 or N400, but to opt for a more exploratory approach to distilling information from EEG signals in a complex experimental design that allows us to capture and interpret both amplitude and time shift effects. The details of that approach are explained in Section 3.

2. Lexical decision: behavioural measures

2.1. Method

2.1.1. Participants

Forty right-handed non-native listeners of English (mean age: 20.9 years, min.: 18, max.: 28) participated in the experiment. All were native speakers of Dutch and master students of English-taught degrees at Radboud University. None of the participants had any hearing disabilities or neurophysiological disorders, and all were paid for their participation. The study was approved by the local ethics committee, and the participants' written consents were obtained prior to participation.

2.1.2. Stimuli

Stimuli were created for the poststress and prestress conditions.

The 400 acoustic stimuli used for the poststress condition were taken from Mulder et al. (2015). Of these stimuli, five filler words were replaced by other filler words as these were also used as targets in the prestress condition. All poststress target words were trisyllabic and had main stress on the first syllable and a schwa in the second syllable. Word stress in the cognates' Dutch equivalents was always on the *third* syllable (e.g. English /ˈɪmpətənt/ versus Dutch /ɪmpoˈtɛnt/ for impotent).

The choice of the prestress stimuli was slightly more involved. To investigate whether the fact that native speakers of Dutch are highly familiar with words that start with a "weak–strong" pattern affects the way in which they handle "weak–strong" words in a lexical decision experiment with English stimuli, it is not necessary to limit all stimuli to three-syllable words. Therefore, we decided to select words with two, three or four syllables. This gave more flexibility and made it possible to find a larger number of cognates.

In total, we used 500 stimuli in the prestress condition: 250 real mono-morphemic English words and 250 pseudowords. Of the 250 real English words, 136 were target items, and 114 were filler items. The target items were 68 Dutch–English cognate items and 68 English non-cognate items. An item was considered a cognate if it had the same meaning in English and Dutch and a large overlap in form in these languages. To determine the amount of form overlap, we calculated the Levenshtein distance (not considering word stress) between the Dutch and the English phonemic representations. We did not correct for word length because there are other important factors that affect the actual duration of the spoken words than the number of segments (i.e. vowel length, stress pattern) which are not accounted for when dividing the Levenshtein distance by the number of segments. Therefore, we decided to go for the raw Levenshtein measure. If the Levenshtein Distance was <5, the item was considered a cognate (for cognates, the mean distance was 3.3 for the prestress condition, compared to 3.7 in the poststress condition; for non-cognates these values are 5.1 and 5.5, respectively). Primary word stress was on the second syllable in both the English targets words and their Dutch equivalents (e.g. English /mənˈuːvər/ (maneuver) versus Dutch /manˈœːvrə/ (manoeuvre).

The cognates and non-cognates had similar log subtitle word frequencies in SUBTLEX-UK (van Heuven et al., 2014); mean frequency for cognates and non-cognates in the prestress condition: 3.84 and 3.63, respectively; in the poststress condition: 3.89 and 3.96, respectively.[2] Apart from frequency, cognate status and length, we did not control for other variables such as neighbourhood density. Controlling for neighbourhood density was not possible because the sets of poststress and prestress cognates and controls were restricted. Moreover, it is not clear what role phonological neighbourhood density plays in auditory word recognition. Effects of neighbourhood density are found to be dependent on a cocktail of many different factors (Mulder, van Heuven, et al., 2018). Moreover, it is not evident how this measure must be calculated: which neighbours should be included in auditory experiments? Only focus on onset neighbours? Only substitution neighbours or also addition, deletion etc.? What about their frequency? Therefore, we decided to focus on the most important variables that have robust effects, such as frequency.

The filler items in the prestress condition were 44 disyllabic, 48 trisyllabic and 22 four-syllabic real words, with the position of word stress varying between words. These filler items were matched to the set of experimental items on number of syllables and frequency of occurrence. The pseudowords were generated by means of Wuggy (Keuleers & Brysbaert, 2010) on the basis of the target and filler words. The pseudowords were phonotactically legal in English.

All stimuli were recorded by the same male native speaker of British English who produced the poststress stimuli used in Mulder et al. (2015). Each target word was recorded twice: once in its full form and once without the schwa. In a small proportion of the reduced prestress items more elements than the /ə/ may be missing; for example, the reduced version of the word `professor` sounded as /pfɛsər/. All tokens (full and reduced) were checked by a different native speaker of English and judged as acceptable pronunciations of the words. All prestress and poststress target words and the phonemic transcriptions of the reduced forms are listed in Appendix A. Transcriptions of the pronunciation of the full forms were always compatible with "received pronunciation".

The mean intensities of all stimuli were scaled to 70 dB. The duration of the schwa was manually measured per item with the speech analysis software package *Praat* (Boersma & Weenink, 2019). Schwa was absent in

Table 1. Stimulus duration (in ms) averaged per condition.

	Pre-stress				Post-stress			
	Cognates		Control		Cognates		Control	
	Full	Red	Full	Red	Full	Red	Full	Red
Schwa duration	46.16	0	39.85	0	66.64	0	63.63	0
Word duration	587.1	464.0	668.1	480.8	665.85	510.23	660.41	494.15

all reduced forms (see Table 1). The schwas in the full forms of the prestress condition are shorter than their counterparts in the poststress condition.

We created 20 experimental lists on the basis of these materials. In half of the lists, the block with stimuli from the prestress condition preceded the block with stimuli from the poststress condition, and in half of the lists this order was reversed. The order of the words in the block was pseudo-randomised. In each list, no more than three real words or three pseudowords occurred in a sequence and half of the target words were full and the other half reduced. The 20 lists were then mirrored in the reduction status of the target items, resulting in a total of 40 lists. As a result, each list and each block contained a different combination of reduced and full-form cognates and non-cognates. During the experiment, each list was split into two halves, with a break in between.

The chosen experimental design has the factor "reduction" nested under "cognate" and "control", but absent under "filler" and "pseudoword".

2.1.3. Procedure

Participants performed an auditory lexical decision task. They were asked to decide as quickly and accurately as possible whether or not the aurally presented stimulus was a real English word by pressing a button. Participants pressed the "yes" button with their dominant hand. Participants first read the instructions (in English), which informed them about the procedure of the task, followed by a practice session containing six items (one reduced non-cognate, one full cognate, one full non-cognate, and three pseudowords), which were not part of the actual experiment.

Table 2. Mean accuracy scores and standard deviations (in parentheses) in the post-stress and pre-stress conditions. The size of the reduction and cognate effects are also shown.

		Full	Reduced	Reduction effect
Pre-stress	Cognate	84.99 (9.01)	61.9 (12.34)	−23.09
	Non-cognate	78.25 (10.79)	59.82 (11.57)	−19.33
	Cognate effect	+6.74	+2.08	
Post-stress	Cognate	92.51 (7.29)	78.25 (10.64)	−14.27
	Non-cognate	90.1 (8.3)	81.16 (11.59)	−9.7
	Cognate effect	+2.41	−2.78	

The task was developed and conducted in `Presentation` version 16.5.[3] Each trial started with the presentation of a black fixation marker "+" in the middle of a grey screen for 400 ms. Then the target stimulus was played. The fixation marker remained on the screen, so that participants had a clear focus point during the trials and felt no need to make head and eye movements. Each trial terminated when the participant had pressed a response button or after a time-out of 5000 ms measured from stimulus onset. Then, a blank transition screen of 500 ms was presented before the start of the next trial.

After completing the lexical decision task, participants performed the LexTALE proficiency task (Lemhöfer & Broersma, 2012). LexTALE is a standardised test designed to assess the vocabulary knowledge for medium- to highly proficient learners of English as a second language, and provides an indication of the participants' general proficiency level in English. The participants were highly proficient in English as evidenced by their scores on the LexTALE task (mean = .83, SD = .37). Nevertheless, in a preprocessing step prior to the analysis (see below), four participants were excluded from analysis because of their high error rates (>30%).

2.2. Results

Time outs were treated as "missing data". All stimuli with reaction times (RTs) shorter than 300 ms or longer than 2.5 times the overall standard deviation above the grand mean were removed from the data set.

The chosen experimental design, with the factor "reduction" nested under "cognate" and "control", but absent under "filler" and "pseudoword", does not allow for a straightforward statistical analysis taking all data into account. Therefore, we limit ourselves to an analysis in which the fillers and pseudowords were omitted. This step resulted in a data set of 6357 trials. From this set, a smaller data set of 5029 trials was constructed by leaving out all incorrect responses. The accuracy analysis was done on the 6357-trial set, while the RT analyses were done on the 5029-trial set. Although it can be argued that a model should account for all RT values, irrespective of whether the decision was right or wrong (e.g. Baayen & Milin, 2010; Lo & Andrews, 2015; ten Bosch et al., 2019), we decided that here the RT model should be limited to the RT values associated with the correct decisions. The reason is that we are especially interested in the effect of the factor `cognate`; if an item is not recognised as a real word, it is highly unlikely that the (non-)cognate status of that item can have an effect.

2.2.1. Accuracy data

Table 2 presents the mean accuracy scores on reduced and full cognates and non-cognates in the prestress and poststress conditions. The data suggest a strong effect of the factors `condition` and `reduction` and a smaller effect of the factor `cognate`. The data were analysed with logistic linear mixed effect models, using the package `lme4` (Bates et al., 2015), with participant (henceforth abbreviated as `ppn` throughout) and item (word) as cross-random effects in `R version 3.5.1`. In the accuracy analyses, the following factorial predictors were considered: `Reduction` (reduced or full), `Cognate` (cognate or non-cognate) and `Condition` (prestress or poststress). Further, we considered the following numerical predictors: the logarithm of `stimulus duration`, `Trial` (the rank of the item in the stimulus list of a condition), `Block` (1 or 2, first or second part of the experiment), word frequency `corpusLogFrequency` (van Heuven et al., 2014), and a logarithmic representation of reaction time (`logRTcor`, see below for more detail).

Table 3. Result for final_accuracy_model.

	Estimate	Std. Error	*z* value	*p*	Sig.
(Intercept)	8.7243	1.4148	6.166	6.99e−10	***
cognatecog	−0.2190	0.3615	−0.606	0.544661	
reductionreduced	0.1525	0.3762	0.405	0.685206	
dur_reduction	0.7105	0.1742	4.078	4.55e−05	***
conditionpre−stress	−1.7489	0.4623	−3.783	0.000155	***
block2	−0.8150	0.3441	−2.368	0.017867	*
corpuslogFreq	1.6811	0.1744	9.638	<2e−16	***
logRTcor	−1.4912	0.1674	−8.909	<2e−16	***
cognatecog: reductionreduced	−0.7098	0.1679	−4.228	2.35e−05	***
cognatecog: dur_reduction	−0.8201	0.2428	−3.378	0.000731	***
reductionreduced: dur_reduction	−0.4536	0.1744	−2.601	0.009286	**
cognatecog: conditionprestress	0.9883	0.4771	2.071	0.038323	*
conditionpre-stress: block2	0.4230	0.6017	0.703	0.481986	
cognatecog:block2	1.0278	0.2771	3.710	0.000208	***
reductionreduced: corpuslogFreq	−0.4641	0.1081	−4.295	1.75e-05	***
cognatecog: reductionreduced: dur_reduction	0.7662	0.2505	3.059	0.002224	**
cognatecog: conditionpre-stress: block2	−1.2734	0.3274	−3.890	0.000100	***

Notes: In "cognatecog", the suffix "cog" represents the level "cognate" of the categorical predictor `cognate`; the level "non-cognate" is on the intercept. For the two-level categorical predictor `reduction`, the level "full" is on the intercept, while for the two-level categorical predictor `condition`, "poststress" is on the intercept.*** $p < 0.001$; $**\tilde{}$p< 0.01; * *p*<0.5; . $p \leq 0.1$.

The regression model was the result of first establishing the fixed structure in combination with an intercept-based random structure, after which the random structure was enriched by including predictors of interest as slopes, taking into account the convergence properties of the resulting regression model. In case of a serious collinearity in terms of high correlation, we residualised predictors. We agree with Matuschek et al. (2017), who argue that random effect structure should be fitted to the data, by including the variance components for participant- and item-related intercepts and fixed effects, and correlations between all random effects. The random effect structure was reduced if and only if the resulting model did not converge by the standard one-vote convergence criterion. We believe that this provides a workable solution to the Type 1/Type 2 error balance issue. Our reasoning is in line with the argument in Matuschek et al. (2017) and Bates et al. (2018) that a selection of a theoretically defendable parsimonious linear mixed effect model is a reasonable alternative to a maximal model. The conclusions of Matuschek et al. (2017) are based on simulation scenarios; with data from an actual experiment one should follow a theoretically founded model optimisation path in which the use of convergence criteria based on a multiple voting by using different optimisers is a practical way to proceed.

In all cases the correlation (collinearity) between two predictors within a regression model was checked. In Wurm and Fisicaro (2014) an overview is presented of the effect of correlation for the quality and interpretability of resulting models. In general, a certain degree of collinearity between predictors may lead to a loss of statistical power of tests on the individual regression slopes, but at the same time it is observed that collinearity per se is not necessarily bad (for a recent account see García et al. (2020)). In our models, only reduction (a two-level factor variable) and log(stimulus duration) (a continuous variable) were medium correlated (0.65). We therefore decided to residualise `log(stimulus duration)` over `reduction`, in line with Wurm and Fisicaro (2014) and Matuschek et al. (2017). The resulting (continuous) predictor `dur_reduction` replaces the original predictor `log(stimulus duration)` in the statistical models. This residualised predictor models the effect of the logarithm of the stimulus duration after removal of the effect of the factor `reduction`.

The coding was chosen such that the intercept would represent the grand mean (this is not essential, but it makes the interpretation of model output easier). The reference level represents the values `control, full` form, block 1, and poststress. The random factors that were included in the stepwise variable selection procedure were all predictors of interest. The final models were tested against overparameterisation in the way described in Matuschek et al. (2017), via a model criticism phase based on $\sigma = 2$ exclusion of outliers, in line with Gelman and Hill (2006).

The final model had the following structure:

```
final_accuracy_model = glmer(Correct~cognate*reduction*dur_reduction +
   condition*cognate*block+corpuslogFreq*reduction+block+logRTcor+
   (1|ppn)+(1|item), family = binomial, data = dat,
   control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=100000)))
```

Inclusion of control requirement settings in control and optCtrl was needed to make the model converge properly.

The output of our final model is shown in Table 3. First of all, it can be seen that longer words (length corrected for reduction) are scored significantly more accurately than shorter words, but this accuracy gain is smaller or absent for cognates, as well as for reduced items. As expected, there is a highly significant speed-accuracy trade-off (see logRTcor) that holds irrespective of all other factors. Equally unsurprising, there is a very significant effect of word frequency, but the negative beta of the interaction reductionreduced:corpuslogFreq shows that the facilitatory frequency effect is weaker for reduced forms.

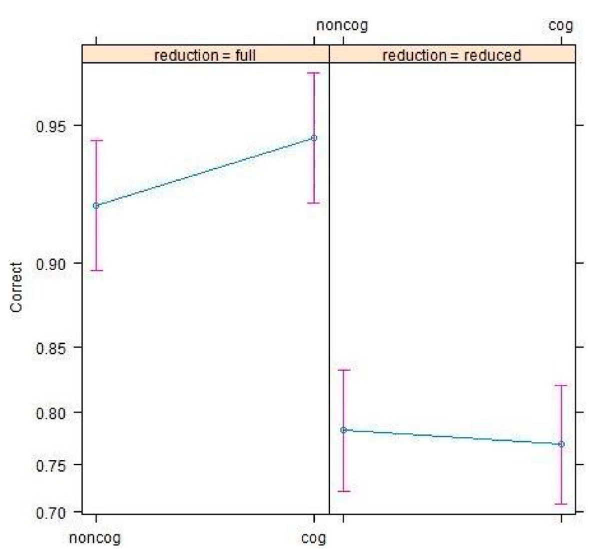


Figure 1. Partial effects plot of the interaction between the factors cognate and reduction in model final_accuracy_model.

The significant effect of block2 is more difficult to explain. In several trial experiments, participants reported that they did not experience any fatigue, despite the large (900) number of items in the experiment. Also Winsler et al. (2018), who conducted two experiments in which participants listened to over 1000 stimuli for lexical decision or semantic categorisation, do not report fatigue effects. Still, the negative beta of the factor level block2 suggests an overall fatigue effect. However, the positive beta of the interaction cognatecog:block2 points towards a learning effect that benefits cognate stimuli, but the negative beta of the three-way interaction of cognatecog, conditionprestress and block2 shows that this learning effect is diminished for prestressed cognate stimuli if they occur in the second part of a session.

Accuracy in the *prestress* condition is lower than in the *poststress* condition. This corroborates LoCasto and Connine (2002), who also found that the (shorter) *prestress* stimuli caused more difficulties for their participants.

The main factors cognate and reduction are not significant as simple effects, which is especially surprising for reduction that shows much lower accuracy percentages in Table 2. However, there is a significant interaction between cognate and reduction, with a negative beta. The interaction is summarised in the partial effects plot shown in Figure 1.[4] The left-hand part shows the interaction for the "full" stimuli, where cognate status increases accuracy. The right-hand part shows the interaction for the "reduced" stimuli. Apparently, in the reduced stimuli cognate status does not improve accuracy; if anything, is hurts slightly. The detrimental effect of reduction on the recognition of cognates is mitigated by the duration of the stimuli, as can be seen from the significant three-way interaction. From the numbers that we have it is not possible to decide whether the very similar accuracy percentages for reduced cognates and controls in Table 2 mean that there is insufficient form overlap for a cognate effect to occur, or, alternatively, whether the much larger decrease in accuracy of the reduced cognates compared to reduced controls indicates that cognate status does play a role and negatively affects the processing of reduced words. The positive beta of the three-way interaction cognatecog:reductionreduced:dur_reduction might indicate a preference for the former interpretation: as the amount of acoustic information increases, the detrimental effect of the cognate status decreases.

2.2.2. RT analysis

The analysis of seemingly simple data as RTs is fraught with methodological and interpretational difficulties (e.g. Baayen & Milin, 2010; Lo & Andrews, 2015). Linear RT distributions are almost always (heavily) skewed to the right. Many approaches use some kind of non-linear transformation to reduce skewness and make the distributions more Gaussian. However, logarithmic or inverse transformations make that the data no longer can be considered as taken on a ratio scale. This may have drastic consequences for the underlying theoretical model (see the discussion in Lo & Andrews, 2015). For our experiment, we do not have assumptions or predictions that depend on RTs being strictly linear.

Some researchers define RT as the time between the start (onset) of a stimulus and the response moment; others prefer the time between the end of the stimulus (offset) and the response moment. As long as the durations of the stimuli are very similar (if not equal) the difference between RT_{onset} and RT_{offset} is negligible. However, in auditory lexical decision experiments the durations of the stimuli can vary considerably. Leaving out the four extreme values, because these might distort the overall picture, the durations of the full stimuli range from 440 to 900 ms, while the durations of the reduced stimuli range from 310 to 800 ms (also see Table 1). Mulder et al. (2015) used the time from stimulus *offset* in their analysis of RTs. Here, we will compare the results of analyses with RT_{onset} and RT_{offset}.

Most procedures for analysing RTs approach RT values as unordered sets, but include "previous RT" as predictor to account for the fact that RTs are actually recorded as a sequence. The "previous RT" is invariably a very significant predictor with large effect size. In ten Bosch et al. (2014, 2018), a proposal was made to process RT as sequences in order to remove ("filter") long-term and medium-term effects that obscure the short-term effects of individual stimuli that we are actually interested in.

If RTs are considered as time series, handling "missing values" becomes more important and more difficult than when RTs are treated as independent measures without any sequence interpretation. There is an extensive literature on treating missing values in time series (e.g. Pratama et al., 2016; Yozgatligil et al., 2013), mainly originating from disciplines such as Economics and Climatology. One thing that virtually all approaches have in common is that they infer missing values based on a statistical model of a sequence of preceding values, much like the filtering approach in ten Bosch et al. (2014, 2018).

In this paper, we used a relatively simple method for preparing the observed raw RTs for further processing. First, all items for which no response was recorded, or with $RT<300$ ms after stimulus onset were given the median linear RT value of the valid items of a participant in the relevant condition (*prestress/poststress*). This step is not used for outlier selection, but just for facilitating the subsequent RT sequence processing steps while maintaining the sequence interpretation. Next, the medium- and long-term trends in the RT sequences were removed by subtracting a fifth-order Chebyshev fit ("detrending"). The resulting sequence of a condition is split in two equal parts corresponding with the breaks in the experiment, and for each part we compute an upper and lower bound as $median \pm 3.0 \cdot mad$, where *mad* stands for "median absolute deviation" (Huber, 1981). Then, the original absolute linear level is repaired by adding the Chebyshev fit. This sequence of steps results in an RT sequence with so called "local speed effects" removed, while preserving the fine-grained local structure in the observed RT sequence. Information about the stimuli for which no valid response was recorded was preserved, so that these can be excluded in subsequent statistical analyses. This procedure was the same for onset-based and offset-based RTs.[5]

2.2.3. The procedure followed in building `lmer` models

The cleaned-up RT data were analysed with linear mixed effect models with participant and item as cross-random effects. For the analyses, the same factorial and numerical predictors were considered as in the accuracy analysis. We added two additional predictors that account for the effects caused by a number of preceding stimuli (the so called local speed effect). The predictor `BVis01` for stimulus n counts the number of stimuli preceding stimulus $n-1$ up to the first one that has an RT value greater than the RT of stimulus $n-1$, indicated as the "backward visibility" (ten Bosch et al., 2019). When the RTs adhere to a Gaussian-like distribution, the number of RT values to the left "that can be seen" will vary within a small range. However, if a preceding stimulus happens to have a very large RT value, it will block the visibility of all stimuli that preceded it. Therefore, `BVis01` flags exceptional stimuli that precede the present stimulus, and that may affect the present stimulus.

The predictor `maRT` (moving average Reaction Time) is the weighted sum of the RTs of a number of preceding stimuli. The weights in this sum decrease with the lag size to the present stimulus (ten Bosch et al., 2018). This resulting weighted average `maRT` serves as a predictor of the current RT, exactly in the same way as the "previous RT" does in conventional regression models simulating RT. It has been shown that in many cases `maRT` leads to a much better model in terms of AIC than the use of the "previous RT", indicating that the local speed effects have a longer time range than just length 1 (ten Bosch et al., 2018, 2019). It appears that maRT and BVis01, if figuring simultaneously as predictors in a `lmer` regression model, are often both significant. For more details, see ten Bosch et al. (2018, 2019) and references therein.[6]

Recall that we only analyse the RT values of the target stimuli (i.e. the cognates and the dedicated control words) and within that subset only the stimuli that were correctly recognised as a real word.

Table 4 shows the results of an ANOVA on the combined set of correctly judged stimuli in the prestress and poststress conditions. It can be seen that the main factor `condition` (`post` in the Table, with `prestress` on the intercept) is highly significant. Also, the interaction of `condition` and `corpuslogFreq` as well as the four-way interaction `poststr:reduction:dur_reduction:cognate` is significant. Therefore, and given the very different linguistic properties of prestressed and poststressed stimuli (Bürki & Gaskell, 2012), we decided to conduct separate analyses for the poststress and prestress condition, and make a comparison between the two conditions on a higher level of abstraction. The prestress and poststress stimuli were blocked in the design of the experiment, with a substantial break between the blocks. It is justifiable to consider the design as two experiments, be it with the same participants.

In designing `lmer` models for the prestress and poststress data, we used the same procedure as described in Section 2.2.1.

Table 4. Type III Anova table (Satterthwaite's method) showing that a separation of pre-stress and post-stress data is justified, due to the significant interaction between an additional categorial variable `pos` (with levels pre-stress or post-stress), `reduction`, the residualised `dur_reduction`, and `cognate`.

(anova)	Mean Sq	DenDF	*F* value	Pr(>*F*)	
trialindex2	1.855	4985.9	233.5263	<2.2e−16	***
BVis01	0.035	6000.7	4.4485	0.034972	*
maRT	125.416	5737.5	15789.9522	<2.2e−16	***
poststr	0.306	225.4	38.5128	2.580e−09	***
reduction	0.015	5993.6	1.8648	0.172123	
dur_reduction	0.142	363.2	17.8727	2.992e−05	***
cognate	0.006	259.4	0.7785	0.378432	
corpuslogFreq	0.069	223.5	8.7239	0.003476	**
poststr:reduction	0.000	5993.1	0.0008	0.977328	
poststr: dur_reduction	0.002	341.4	0.2024	0.653114	
reduction: dur_reduction	0.027	4246.8	3.4057	0.065039	.
poststr:cognate	0.000	260.3	0.0116	0.914456	
reduction:cognate	0.000	5992.5	0.0020	0.963950	
dur_reduction: cognate	0.000	411.8	0.0226	0.880685	
poststr: corpuslogFreq	0.053	214.8	6.7190	0.010194	*
poststr:reduction: dur_reduction	0.018	4225.6	2.3095	0.128663	
poststr:reduction: cognate	0.001	5990.9	0.1601	0.689104	
poststr: dur_reduction: cognate	0.000	412.6	0.0252	0.874047	
reduction: dur_reduction: cognate	0.003	4486.5	0.3316	0.564728	
poststr:reduction: dur_reduction: cognate	0.064	4484.1	8.1009	0.004444	**

2.2.4. The results with RT_{offset}

RT_{offset} is defined as the logarithm of the difference between the RT of a stimulus and the duration of the acoustic stimulus. In this procedure, 38 stimuli (0.6% of the total number of stimuli) were removed because the difference was zero or negative. The number of stimuli was further reduced by removing those with a value of RT_{offset} outside the range $\mu \pm 2.5 \cdot \sigma$ per participant.

2.2.4.1. The poststress condition.

Our final regression model for the data in the poststress condition is

```
RT.offset.poststress  =  lmer(logRToff-
set~trialindex2+maRT +
  dur_reduction*reduction*cognate + (1|
ppn)+(1|item), data = data,
  control=lmerControl(optimizer="bo-
byqa",optCtrl=list(maxfun=100000)))
```

The results of the model for the poststress condition with RT_{offset} are shown in Table 5. Note that the factor values `control, full form, block 1` are on the reference level.

The negative beta of `dur_reduction` shows that a longer stimulus duration shortens the RT, implying that stimuli that contain more acoustic information take less processing time after stimulus offset. `Reduction` as main factor is associated with longer RTs, especially for longer stimuli, but that latter effect is mitigated for cognates (see the three-way interaction `dur_reduction:reductionreduced:cognatecog`). As a main factor `cognate` is not significant, but its interaction with reduction and stimulus duration shows that cognate has a complex effect on RT.

The interaction `dur_reduction:reductionreduced` is associated with longer RTs; reduced stimuli benefit less from more acoustic information than fully produced stimuli. The interaction `dur_reduction:cognatecog` is also associated with longer RTs. This might mean that the effect of L1–L2 co-activation is inhibitory, rather than facilitatory (the effect of this is

Table 5. `lmer` model for the poststress condition with RT measured from stimulus offset.

	β	Std. err	t	p	Sig.
(Intercept)	6.054e+00	4.725e−02	128.121	<2e−16	***
trialindex2	−3.438e−04	3.907e−05	−8.801	<2e−16	***
maRT	1.883e+00	2.122e−02	88.754	<2e−16	***
dur_reduction	−1.549e+00	8.105e−02	−19.117	<2e−16	***
reductionreduced	3.789e−01	1.265e−02	29.950	<2e−16	***
cognatecog	5.856e−03	1.540e−02	0.380	0.70407	
dur_reduction:reductionreduced	6.482e−01	8.978e−02	7.220	6.85e−13	***
dur_reduction:cognatecog	2.155e−01	1.046e−01	2.061	0.03977	*
reductionreduced:cognatecog	−8.350e−03	1.764e-02	−0.473	0.63604	
dur_reduction:reductionreduced:cognatecog	−3.674e−01	1.254e−01	−2.929	0.00344	**

modulated by the amount of reduction, as shown by its three-way interaction with `reduction`).

The predictor `BVis01` was not significant. Since it didn't figure in significant interactions either, it was left out from the model. Apparently there are few exceptional stimuli in the poststress condition.

2.2.4.2. The prestress condition.
For the data in the prestress condition we followed the same model selection procedure as outlined above. The final model is:

```
RT.offset.prestress = lmer(logRToffset~-
trialindex2 + BVis01 + maRT +
  dur_reduction* reduction  +  dur_reduc-
tion* cognate + dur_reduction +
  corpuslogFreq +  (1|ppn)+(0+dur_reduc-
tion|ppn) + (1|item), data = data,
  control=lmerControl(optimizer="bo-
byqa",optCtrl=list(maxfun=100000)))
```

The result of the model is shown in Table 6.

There are some interesting differences between the prestress and poststress models. Most conspicuously, `BVis01` is highly significant in the prestress condition. This suggests that there are stimuli in the prestress stimuli that significantly affected subsequent stimuli at least for some listeners. The effect of `reduction` is somewhat smaller than in the poststress condition. Finally, the interaction `dur_reduction:reduction:cognatecog` that was significant in the poststress condition lost its significance in the prestress condition (and was therefore left out from this latter model). Overall, these differences suggests that the effect of cognate status of stimuli differs between the prestress and poststress conditions.

2.2.4.3. Intermediate discussion.
The most striking result of the analysis of the data with RT_{offset} is that the duration of the stimuli has a very large effect with a negative beta. Apparently, the time that is needed to decide whether a stimulus is a real word becomes shorter if more acoustic information has accumulated during the unfolding of the stimuli. From the positive beta for the interaction `dur_reduction:reductionreduced` it can be deduced that the duration effect is larger for the full than for the reduced stimuli, and the effect seems stronger in the poststress condition.

Interestingly, the prestress condition reveals no significant interaction of cognate with reduction, while in the poststress condition cognate and reduction are only found to interact significantly in a three-way interaction with `dur_reduction`. In both conditions, cognate only interacts with `dur_reduction`. This might suggest that, due to reduction, the overlap between representations in the prestress condition was not enough to trigger co-activation. For the poststress condition, it seemed there was enough overlapping information to trigger a co-activation effect, and the longer RTs associated with the interaction `dur_reduction` and cognate status shows that this effect is inhibitory. The effect of reduction then diminished this cognate effect.

Table 6. `lmer` model for the prestress condition with RT measured from stimulus offset.

	β	Std. err	t	p	Sig.
(Intercept)	6.355e+00	5.080e−02	125.096	<2e−16	***
trialindex2	−3.414e−04	2.851e−05	−11.975	<2e−16	***
BVis01	−9.017e−03	2.300e−03	−3.920	9.02e−05	***
maRT	1.828e+00	2.253e−02	81.125	<2e−16	***
dur_reduction	−1.314e+00	5.848e−02	−22.467	<2e−16	***
reductionreduced	3.399e−01	8.113e−03	41.896	<2e−16	***
cognatecog	5.544e−03	1.160e−02	0.478	0.63346	
corpuslogFreq	−4.195e−02	6.401e−03	−6.554	9.89e−10	***
dur_reduction:reductionreduced	2.180e−01	4.873e−02	4.474	8.03e−06	***
dur_reduction:cognatecog	1.783e−01	6.041e−02	2.952	0.00344	**

The predictor corpuslogFreq is significant, with negative beta, in the prestress, but not in the poststress condition. This would suggest that stimuli that are overall more difficult to process benefit more from familiarity.

The fact that BVis01 is significant in the prestress, but not in the poststress condition may suggest that the set of prestress stimuli contains a number of pronunciations that struck at least some listeners as exceptional.

2.2.5. The results with RT_{onset}

Also for the RTs measured from stimulus onset it appeared from an ANOVA analysis (not shown here) that condition as well as a number of its interactions (including reduction) were significant, so that it is justified to split the data and to build separate models for the prestress and poststress data.

2.2.5.1. The poststress condition.

The final model for the data in the poststress condition is

```
RT.onset.poststress = lmer(logRTcor~-
trialindex2 + maRT +
  reduction*dur_reduction*cognate + (1|
ppn)+(1|item), data = data,
  control=lmerControl
(optimizer="bobyqa"))
```

The results are in Table 7. Similar to the offset models, the reference level of the model represents the factor values control, full form, block 1.

The model has the same structure as the model for the poststress condition for RT_{offset}, but the significance profile is less pronounced. The only truly significant interaction is the three-way interaction reductionreduced:dur_reduction:cognatecog. Its beta has the same sign as the corresponding interaction for RT_{offset}. Note that the sign of the beta of (the non-significant) dur_reduction is opposite to the sign of this predictor in the model for RT_{offset}.

2.2.5.2. The prestress condition.

The best model in the prestress condition is

```
RT.onset.prestress = lmer(logRTcor~tria-
lindex2 + BVis01 + maRT +
  reduction*dur_reduction*cognate + cor-
puslogFreq +
  (1|ppn) + (1|item), data = data)
```

Adding random variables under ppn does not improve the AIC. The result is shown in Table 8.

Again, we see that corpuslogFreq is significant, with a negative beta (more frequent stimuli are associated with shorter RTs). The residualised predictor dur_reduction is significant with a positive beta, which is modulated by the significant interaction with reduction. Note that these signs are opposite to what we found with RT_{offset}. The factor cognate now appears in the significant three-way interaction with reduction and dur_reduction.

2.2.5.3. Discussion.

The results of the RT models with respect to the interaction between the factors reduction and cognate are summarised in the partial effects plots in Figure 2 for RT_{onset} (top row) and RT_{offset} (bottom row). The left-hand column shows the results for the prestress condition, the right-hand column for the poststress condition. The left-hand part in individual panels shows the interaction in the "full" stimuli; the right-hand part shows the interaction in the "reduced" stimuli. The first thing that strikes the eye is that the variance in the RT_{onset} data is larger than in the RT_{offset} data. It is also obvious that the impact of the factor reduction is much more clear when using RT_{offset}. At the same time, it is clear that the effect of the factor cognate is small in the RT_{onset} data, and practically absent in the RT_{offset} data.[7]

A direct comparison between prestress and poststress data is justified by the fact that the ANOVA tables contain a significant four way interaction with condition (see the ANOVA table 4). This strongly suggests a difference is processing between poststress and prestress stimuli, reflected in a different significance profile of various predictors (especially the three-way) in the corresponding statistical models.

The fact that BVis01 is significant in the prestress condition (with both RT measures), while it is non-significant for poststress provides anecdotal evidence for a difference in processing difficulty that may be related to specific properties of some of the stimuli.[8]

The predictor corpuslogFreq is significant with a negative beta (frequent stimuli yield shorter RTs), for both RT_{onset} and RT_{offset} in the prestress condition, but not in the poststress condition. Because of the small differences in average frequency of the stimuli used in the two conditions (see Section 2.1.2) it appears that especially high-frequency prestress stimuli are easier to process. Since the advantage of high-frequency stimuli occurs with both RT measures, it is not possible to attribute the effect to phonetic decoding or lexical-semantic access (Dahan et al., 2001). But because stimulus frequency is significant in the prestress, but not in the poststress data does suggest a contribution of more difficult phonetic decoding in the prestress condition.

Table 7. `lmer` model for the poststress condition with logRT measured from stimulus onset.

	β	Std. err	t	p	Sig.
(Intercept)	7.009e+00	1.993e−02	351.605	<2e−16	***
trialindex2	−1.253e−04	1.399e−05	−8.954	<2e−16	***
maRT	8.507e−01	7.859e−03	108.251	<2e−16	***
reductionreduced	−1.739e−03	4.577e−03	−0.380	0.7040	
dur_reduction	6.849e−03	2.681e−02	0.255	0.7985	
cognatecog	4.182e−04	5.113e−03	0.082	0.9349	
reductionreduced:dur_reduction	6.147e−02	3.166e−02	1.942	0.0523	.
reductionreduced:cognatecog	−3.485e−03	6.389e−03	−0.545	0.5855	
dur_reduction:cognatecog	5.994e−02	3.499e−02	1.713	0.0874	.
reductionreduced:dur_reduction:cognatecog	−1.071e−01	4.447e−02	−2.409	0.0160	*

2.3. Discussion of the behavioural data

2.3.1. Accuracy

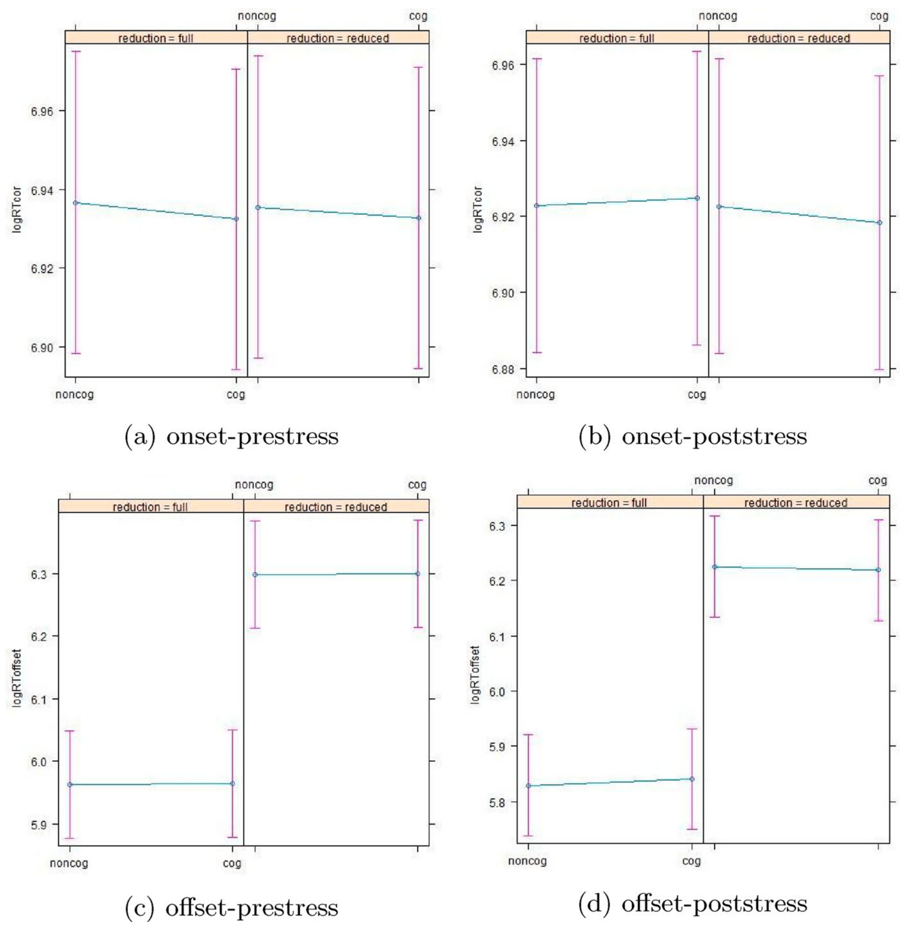
The first question that we addressed in this experiment is whether native speakers of Dutch, who are highly familiar with weak-strong stress patterns in past participle forms where the leading weak syllable is often heavily reduced, would fare better in recognising reduced weak-strong words than the native English participants in LoCasto and Connine (2002). The answer is clearly negative. For all stimulus types, cognates and controls, as well as full and reduced forms, the accuracy scores were significantly lower in the *prestress* than in the *post-stress* condition. In an incremental activation model such as DIANA (Nenadić & Tucker, 2018; ten Bosch et al., 2015), this finding can be explained by the fact that a reduced first syllable, i.e. an acoustically less distinctive start of the stimulus, makes it more difficult to whittle down the set of partially matching words shortly after the start of the stimulus. A reduced first syllable therefore clearly complicates the decision whether a word candidate can be declared the winner in the on-line word competition process. As a result, the risk increases that at the end of the stimulus no lexical candidate stands out sufficiently clearly to be positively identified. Importantly, this effect would occur regardless of the presence or absence of reduced forms in the mental lexicon.

In the literature on bilingual word comprehension in the visual modality, cognate status is generally found to result in higher accuracy scores and faster reaction times (e.g. Caramazza & Brones, 1979; Dijkstra et al., 1998, 1999, 2010; Dufour & Kroll, 1995; Lemhöfer et al., 2008; Schwartz et al., 2007; Voga & Grainger, 2007), but there is also evidence for a beneficial effect of cognate status in the auditory modality (Marian & Spivey, 2003). In addition, neurophysiological studies report less negative N400 amplitudes for cognates than for non-cognate controls (e.g. FitzPatrick & Indefrey, 2010). But it also appears that the beneficial effect of cognate status decreases with deceasing degree of form overlap (Dijkstra et al., 2010). For auditory representations, the form overlap might be weaker and more variable than for printed character strings. The degree of form overlap for Dutch–English cognates is likely to differ between full and reduced pronunciations. Therefore, we asked the question whether reduction affects cognates differently than control words with similar phonetic structure and lexical frequency.

Overall, there was a clear detrimental effect of reduction on the accuracy in the lexical decision task: reduced forms always resulted in lower accuracy. This is in line with earlier studies showing a processing advantage for full forms in isolation (e.g. Ernestus et al., 2002; van de Ven et al., 2012). Yet, the picture is complicated by the two-way interaction `cognate:reduction` that shows that the accuracy of reduced cognates suffers more than the accuracy of reduced control stimuli. Mulder et al. (2015) found the same

Table 8. `lmer` model for the prestress condition with logRT measured from stimulus onset.

	β	Std. err	t	p	Sig.
(Intercept)	7.109e+00	2.156e−02	329.754	<2e−16	***
trialindex2	−1.555e−04	1.074e−05	−14.471	<2e−16	***
BVis01	−2.749e−03	9.031e−04	−3.043	0.00236	**
maRT	8.490e−01	8.735e−03	97.199	<2e−16	***
reductionreduced	−2.590e−03	4.538e−03	−0.571	0.56822	
dur_reduction	6.049e−02	2.436e−02	2.483	0.01344	*
cognatecog	−4.893e−03	4.879e−03	−1.003	0.31680	
corpuslogFreq	−9.831e−03	2.160e−03	−4.552	1.08e−05	***
reductionreduced:dur_reduction	−6.742e−02	2.788e−02	−2.418	0.01569	*
reductionreduced:cognatecog	3.171e−03	6.425e−03	0.494	0.62163	
dur_reduction:cognatecog	−3.075e−02	3.047e−02	−1.009	0.31350	
reductionreduced:dur_reduction:cognatecog	7.837e−02	3.781e−02	2.073	0.03834	*



(a) onset-prestress (b) onset-poststress

(c) offset-prestress (d) offset-poststress

Figure 2. Graphical representation of the effect sizes of the interaction between `cognate` and `reduction` in the models for Reaction Time. Left column: prestress; right column: poststress. Top row: RT_{onset}; bottom row: RT_{offset}. In each panel the left-hand part shows the interaction for full stimuli, and the right-hand part for reduced stimuli. In the offset-prestress condition, the interaction is (statistically) absent. The vertical axes display log(RT).

effect in an experiment with *poststress* stimuli, which led them to the conclusion that reduced cognate stimuli activate the Dutch representations of those words so strongly that participants no longer recognised these stimuli as English words.

However, our findings are also compatible with an alternative interpretation. From the visual lexical decision literature it appears that the cognate effect hinges on the degree of form overlap. For the full forms, where the degree of form overlap is arguably substantial, we see the expected beneficial effect of cognate status. It may well be that the form overlap for the reduced stimuli is too small to give rise to a cognate effect. Note that it does not follow that reduced forms could not in some way be represented in the mental lexicon. The fine phonetic details involved with reduction may differ between English and Dutch, resulting in forms that only weakly overlap. Perhaps, the finding that the detrimental effect of reduction on the cognate effect is mitigated by the duration of the stimuli indicates that it is indeed the lack of form overlap that explains the absence of the cognate effect. As the amount of acoustic information becomes larger, it may be easier to establish form overlap, and profit from that overlap.

2.3.2. RT analysis

There are substantial, and potentially revealing differences between the models that simulate RT, depending on whether RT is measured from stimulus onset or from stimulus offset. In addition, there are substantial differences between the prestress and poststress condition, especially with RT_{offset}.

2.3.2.1. RT_{onset}. An analysis of RTs measured from stimulus onset shows that neither `cognate` nor `reduction` appear to have a significant impact on the observed RTs as main factors. This does not necessarily mean that these manipulations do not affect the cognitive processes. It is quite possible that the effect of the manipulations is too small to survive the substantial variance in RTs between individual stimuli, individual participants, and individual stimulus orders. This is despite the pre-processing of the RTs to remove the effects of local speed. The significant three-way interaction `reductionreduced:dur_reduction:cognatecog` with a negative beta shows that there is a beneficial effect for reduced cognates for stimuli that contain more acoustic information in the poststress condition. In the prestress condition the same three-way interaction is also significant, but now with a positive beta. This suggests an L1–L2 interference that slows down decisions for longer prestress stimuli.

In the prestress – but not in the poststress – condition the predictor `corpuslogFreq` is associated with a significant shortening of RT_{onset}. Since the frequencies of the target words in the two conditions are very similar, this must mean that the role of lexical frequency in the prestress is different from the one in poststress. With the data that we have it is not possible to decide whether lexical frequency mainly affects phonetic decoding or lexical-semantic access in the prestress condition.

2.3.2.2. RT_{offset}.

With RT measured from stimulus offset, we see a very large effect of `reduction` as main factor, but no significant effect of `cognate` as main factor. In the poststress condition, there is a significant effect of the three-way interaction `dur_ reduction:reductionreduced:cognatecog`. In the prestress condition, only the two-way interaction `dur_reduction:cognatecog` is significant. Again, we see a significant facilitatory effect of `corpuslogFreq` in the prestress condition, whereas that predictor is not relevant in the poststress condition. If we assume that phonetic decoding is essentially complete at the end of the stimuli, it follows that the frequency of the stimuli is mainly affects lexical-semantic access.

Cognate as main factor has no significant contribution but acts significantly in higher-order interaction with duration (`dur_reduction`). The positive beta of `reduction` (obtained after residualisation of stimulus duration over reduction) as main factor suggests that recognising a somewhat unexpected form (a reduced pronunciation of a word spoken in isolation) significantly delays the decision process.

2.3.2.3. RT_{offset} versus RT_{onset}.

Perhaps the most important difference between the models for the two definitions of RT is the finding that `reduction` as main factor is very significant for RT_{offset}, but not for RT_{onset}. Another striking difference between the two RT measures is that the betas of stimulus duration residualised for reduction have opposite signs. The latter observation is discussed in depth in Brand et al. (2021). There it is argued that the larger amount of acoustic information available at the end of the longer stimuli is the best explanation for the negative beta in the RT_{offset}. The cognate status mainly matters in the higher order interactions. Therefore, it seems that the linguistic–phonetic factors `cognate` and `reduction` invoke different cognitive processes during the unfolding of the acoustic stimuli and the process(es) that lead to the expression of the eventual decision. It would require an elaborate computational model of spoken word recognition to be able to link all these differences to the existence of reduced forms in the mental lexicon.

2.3.2.4. Prestress versus Poststress.

With RT_{onset} the factor `reduction` never becomes significant in the poststress condition. In the prestress condition `reduction` is significant as main factor with a positive beta: RTs slow down for reduced prestressed stimuli compared to unreduced prestressed stimuli. Interestingly, both reduction and cognate status act in higher level interactions, again showing the complex way in which cognate status interacts with the stimulus processing.

2.3.3. Summary

Taken together, the accuracy and RT results suggest that access to word representations in isolated conditions, such as lexical decision, proceeds via a bottom-up route because form information needs to be processed first. The quality of the initial acoustic signal (i.e. whether the first syllable is reduced or not) appears to determine the conditions under which other processes can play a role. When reduction affects the very beginning of the word, as in reduced prestress words, listeners are immediately faced with a problem, as it is more difficult to narrow down the set of matching word candidates. This is likely to impede L1–L2 co-activation because the initial overlap is not enough to trigger this activation or alternatively, when one assumes that co-activation does occur, it makes the processing of the reduced form even harder. When reduction occurs later in the word, as is the case in the poststress condition, there might be sufficient overlap to trigger a cognate effect that can overcome the effect of reduction in the second syllable. We observed that reduction diminished the inhibitory effect of cognate status in poststress items.

Mulder et al. (2015), who used RT_{offset}, did not find significant effects of cognate status in the RT data, nor a significant interaction between reduction and cognate status. That is confirmed in the present study: `cognate` never was significant as a main factor; also, the interaction `reduction:cognate` was never significant. As a main factor, `reduction` was only significant in the RT_{offset} data, where it gave rise to longer RTs. This also confirms the findings of Mulder et al. (2015). However, with the RT_{onset} data `reduction` was not a significant main factor. In the poststress data, the three-way interaction `reductionred:dur_reduction:cognatecog` is significant with a negative beta, with both RT measures. Therefore, it is safe to conclude that `cognate` has a facilitatory on reduced stimuli in the poststress condition, provided that these stimuli provide sufficient acoustic information. This is in line with the commonly observed facilitatory effect of co-activation through cognates and supports a semantic explanation of the cognate effect.

In the prestress data the three-way interaction `reductionred:dur_reduction:cognatecog` is only significant for RT_{onset}, but with a positive beta. Most probably, the opposite sign must be attributed to the finding that `red_duration` as a main factor is significant with a negative beta with RT_{offset}, and with a positive beta with RT_{onset}. The two-way interaction `reductionreduced:dur_reducttion` is significant with a negative beta. The combination of these two findings suggests that cognate status may have an inhibitory effect on reduced stimuli.

Clearly, the duration of the stimuli determines to a substantial degree the amount of helpful form overlap that can support L1–L2 co-activation. From the behavioural data alone it is not possible to determine whether L1–L2 co-activation is beneficial or inhibitory, or whether that role may change during the course of processing a stimulus. In the EEG analyses presented in the next section, we will examine the processing over time in more detail by investigating the timing of the effects of reduction and cognate in different EEG frequency bands.

3. EEG analyses

3.1. Methodological preamble

As stated in Section 1.2, our analysis of the EEG signals recorded during the lexical decision experiment does not specifically focus on conventional ERP components such as N100 or N400. The most important reason for a more exploratory approach is the complexity of the design of the experiment that involves multiple interacting cognitive processes, each of which might be connected with some ERP component. Moreover, because of the mix of effects caused by cognate status and reduction, we must anticipate that both factors can affect the magnitude of the amplitude and the timing (latency) of amplitude maxima and minima relative to both the onset and offset of the speech stimuli.

A second reason for opting for a more open, exploratory approach to analysing EEG signals is the uncertainty about the relation between effects observed in EEG signals and the putative underlying cognitive processes (see Kutas and Federmeier (2011) for discussions about possible interpretations of the N400). Because there are no validated physical models of the processes that generate the EEG signals, it is usual (and probably inevitable) that researchers base hypotheses about relations between effects in EEG signals and cognitive processes on psycholinguistic models that may themselves be under discussion. For example, the interpretation of oscillations in the theta band ($4<f<8$ Hz) in Strauß and Schwartz (2017) are based on theories of spoken word comprehension that assume a discrete abstract prelexical representation (e.g. Norris & McQueen, 2008), an assumption that is challenged in recent models by, among others, Arnold et al. (2017), ten Bosch et al. (2015) and Magnuson et al. (2020). Finally, Kösem and van Wassenhove (2017) discuss a large number of seemingly contradictory experimental results against the background of two competing (oscillatory- or gain-based) models of neural activity.

Having said this, we still base interpretations of effects in EEG signals on the widely shared assumption that the amplitude of EEG signals (and therewith the amplitudes of ERPs) correlates with processing effort: larger amplitudes (both positive and negative) are associated with more cognitive effort. Also, the timing of maxima and minima in the amplitude of ERPs is associated with the point in time when the underlying cognitive effort peaks. The interpretation of increasing or decreasing power in narrow frequency bands is more complicated: both power enhancement and power suppression have been linked to cognitive processes.

3.1.1. The impact of using stimuli with different durations

The process for generating ERPs is based on the finding that systematic effects in EEG signals can be uncovered by averaging many individual EEG signals, after time-locking those signals at an event of interest. In auditory lexical decision there is one event that is associated with the same point in time t=0 for all stimuli, viz. the onset of the acoustic stimuli. But stimuli generate a second event, which may be as important as the onset of the acoustic signal, namely the offset of the signal. Processes related to phonetic decoding are completed some 250–300 ms after stimulus offset (Marslen-Wilson & Tyler, 1980), while processes related to lexical-semantic access (and in lexical decision experiments also decision making) may continue during a much longer time interval after stimulus offset. Therefore, it does not come as a surprise that a fair number of behavioural studies that focus on lexical-semantic access measure RTs from the moment of stimulus offset (e.g.Mulder et al., 2015).

Above, it has already been mentioned that reduced pronunciations take longer to activate their semantic networks than the corresponding full forms, and that this time shift may complicate ERP analyses that rely on effects being synchronised after the time-lock moment. The design of our experiments contains an additional factor that affects the synchrony of processes related to stimulus *offset* even more, namely the substantial range of the durations of the acoustic stimuli. Leaving out the four extreme values, the durations of the full stimuli range from 440 to 900 ms, while the durations of the reduced stimuli range from 310 to 800 ms. Therefore, we might not be able to uncover effects related to lexical-semantic processing if we would limit ourselves to time-locking at stimulus onset. Rather, we will combine results of two sets of analyses: one based on time-lock at stimulus onset, and the other based on time-lock at stimulus offset (cf. O'Rourke & Holcomb, 2002). We expect that the time-lock on stimulus offset will minimise the compounding effect of variation in stimulus duration.

3.2. Recording procedure

EEG signals were recorded in all experimental sessions, using 64 active electrodes mounted in an elastic cap (*actiCAP*[9]). Electrode positions were a subset of the international 10–20 system, consisting of eight midline and 50 lateral electrodes. Moreover, an electrode was placed on each of the mastoids and each electrode was referenced online to the left mastoid. The electrooculogram (EOG) was recorded by two vertical electrodes placed above and below the right eye and by two horizontal electrodes. Electrode impedance was kept below 15 kΩ. The EEG and EOG signals were amplified (pass band: 0.02 Hz to 100 Hz), and digitised online with a sampling frequency of 1 kHz. For most analyses the signals were digitally filtered off-line with a linear phase band-pass filter with cut-off frequencies 0.1 Hz and 30 Hz.[10]

The continuous EEG was segmented into stimulus-time-locked epochs, starting 300 ms before target word onset up to 3700 ms after word onset, resulting in a total duration of 4000 ms. Artefacts were rejected with a semi-automatic inspection routine that implemented the rejection criteria in the `BrainVision`© Brain Products (2006) software with default values for all (four) criteria. Twelve participants had to be excluded because of the high number of artefacts in the EEG data (i.e. with more than 30% of artefacts out of the total of 228 target stimuli;[11] mean number of artefacts: 18.8%, range 2.2%–50.4%. The final data set contains 29 participants.

3.3. Modeling EEG signals

While auditory stimuli are playing, EEG signals reflect a combination of exogenous (coming from the sensory input) and endogenous processes. It is reasonable to assume that the exogenous process operates independently of the endogenous processes. Therefore, it is safe to assume that the exogenous process is only dependent on the acoustic stimulus per sé, and not on the type of stimulus (`word/pseudo`, `cognate/control`, `full/reduced`). Figure 3 shows the ERPs of the four target stimulus types (`full` *vs.* `reduced`; `cognate` *vs.* `control` in the two conditions (*prestress vs. poststress*) in the frequency band $0.1<f<15$ Hz for the original EEG signals and for the signals from which the exogenous component was removed by means of subtracting the *mTRF* estimate (Crosse et al., 2016; Mulder, ten Bosch, et al., 2018). Time-lock is on stimulus onset. The mTRF estimate is the linear contribution of the loudness envelope of the audio signal that is present in the EEG signal. Subtraction of the mTRF component from the EEG signal is likely to enhance the contrasts between the endogenous processes associated with different stimulus types. This is confirmed in Figure 3, where it can be seen that the differences between the conditions are much more pronounced in the *mTRF*-corrected representations.[12]

Because the differences between the stimulus types are much clearer for the *mTRF*-corrected traces, we present only statistical analyses for *mTRF*-corrected data.[13] It is interesting to note that the N100/P200 complex that is clearly present in the uncorrected ERPs, has disappeared from the *mTRF*-corrected ERPs. This strongly suggests that the N100/P200 complex is primarily associated with exogenous excitation, rather than to endogenous processes related to word segmentation in continuous speech. More detailed analyses are required to see whether there is a Phonological Mismatch Negativity in the reduced stimuli in the prestress condition.

It is unlikely that the effect of sensory excitation stops immediately after stimulus offset. This is confirmed in Figure 4, which shows the averages and standard errors for the raw traces and the traces after mTRF correction time-locked at stimulus *offset*. It can be seen that the effect of mTRF correction in this case is much smaller than the result shown in Figure 3, but there is still an effect, especially in the time interval immediately

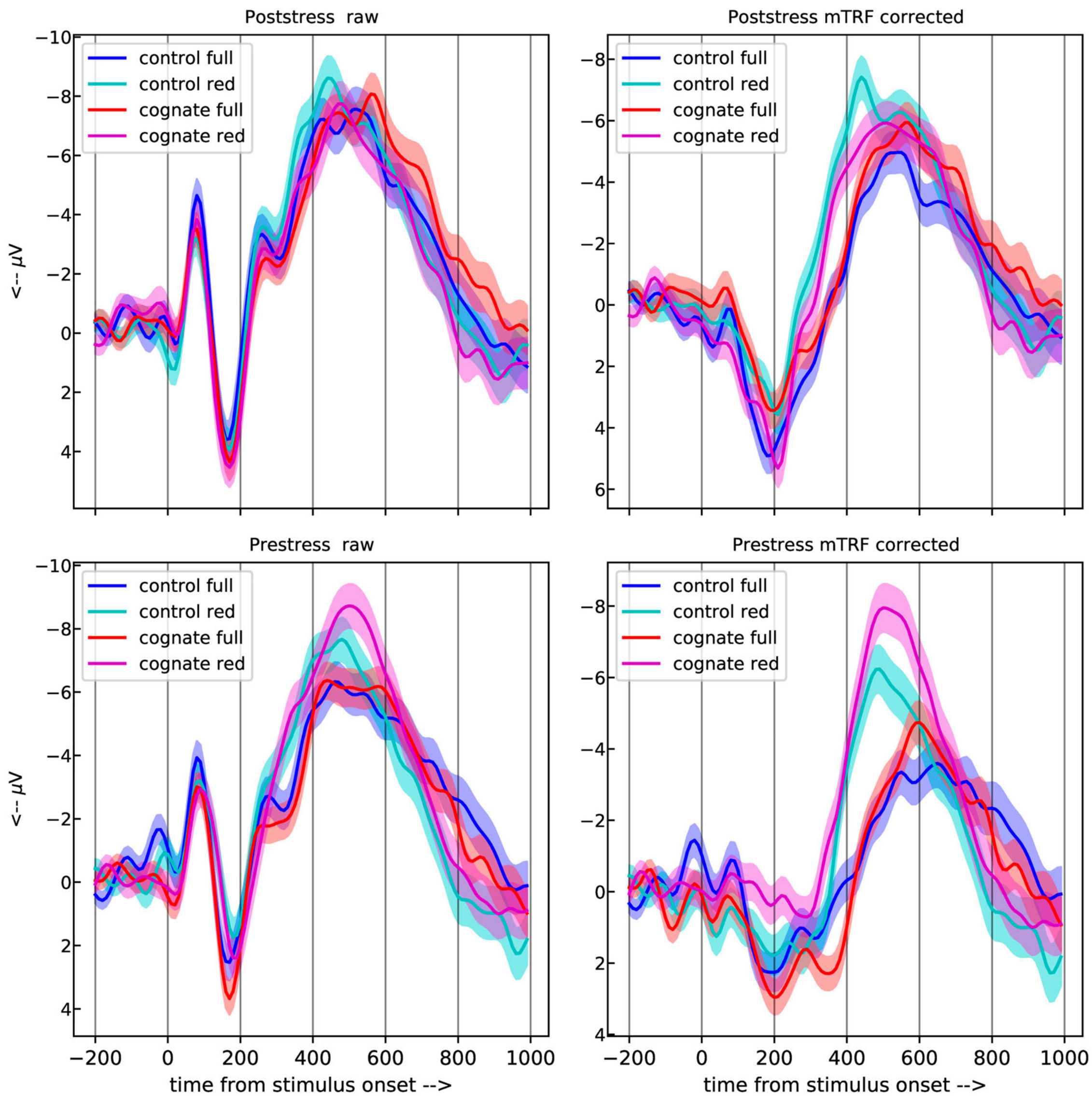


Figure 3. ERPs of wide-band signals for the target stimulus types, time-locked to word-onset; left: raw signals, right: *mTRF*-corrected. Upper panel: *poststress*, lower panel: *prestress*. The bands around the average traces indicate the standard error of the mean.

after stimulus offset. Therefore, we used mTRF-corrected traces in the analysis of the data with time-lock at stimulus onset and stimulus offset.

3.3.1. Choosing the data to analyse

EEG signals have an excellent temporal resolution; as said above, our signals are sampled with a frequency of 1 kHz, which corresponds to a time resolution of 1 ms. At the same time, the spatial resolution of EEG signals, i.e. the precision with which signals can be associated with specific brain areas, is very limited. This is caused by the way in which the electrical potentials in the brain are transmitted to the sensors attached to the scalp. Indeed, most of the data that link cognitive processes to brain areas are derived from magneto-encephalography (MEG) recordings that combine the excellent temporal resolution of EEG signals with excellent spatial resolution. However, this comes at the price of much more expensive and complex experiments.

Because of the limited spatial resolution of EEG signals one invariably sees substantial effects of experimentally controlled factors in most of the sensors. This explains why many psycholinguistic experiments that use EEG limit the analysis to the centrally located sensor *Cz*. If the results are ambiguous, and there is literature that suggests that a specific cognitive process is associated with EEG activity in a specific area of the scalp, additional analyses may disambiguate these effects.

3.3.2. Prestress vs. poststress

A preliminary analysis of ERPs confirmed the (implicit) prediction implied in what was observed before:

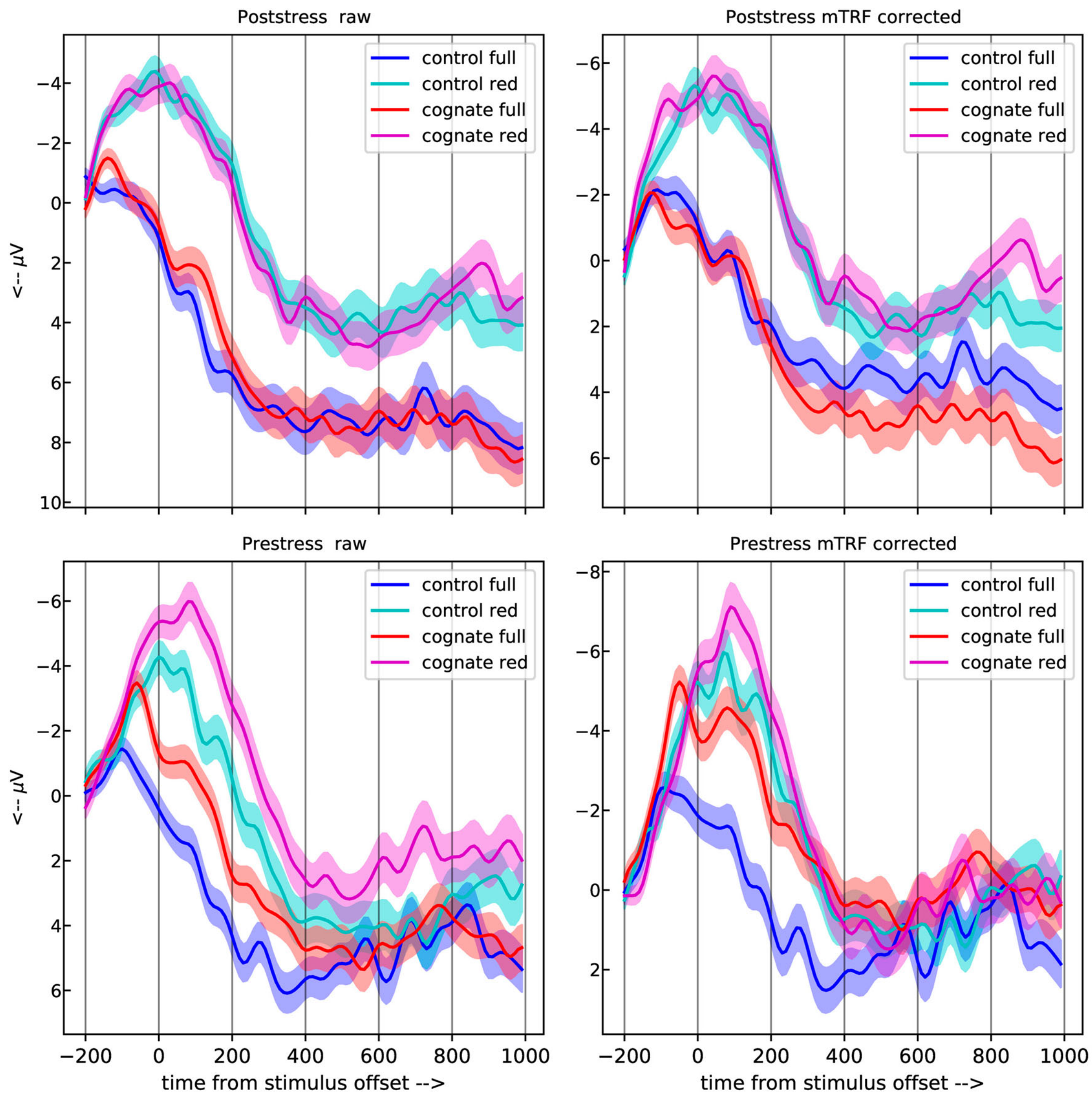


Figure 4. ERPs of wide-band signals for the target stimulus types, time-locked to stimulus offset; left: raw signals, right: *mTRF*-corrected. Upper panel: *poststress*, lower panel: *prestress*. The bands around the average traces indicate the standard error of the mean.

several effects in the prestress condition are delayed by between 100 and 200 ms relative to the effects in the poststress condition. The finding is also confirmed by the ERPs shown in the right-hand column of Figure 3. To avoid the temporal smearing effect due to the systematic delay between prestress and poststress stimuli, we decided to analyse the poststress and prestress conditions separately, and compare and collate the outcomes afterwards in the same way as with the behavioural data.

3.3.3. The case for applying `lmer` analyses

In Mulder, ten Bosch, et al. (2018), the authors experimented with Generalised Additive Models (GAM) to investigate whether sentence-medial reduced words were processed differently from full words in the same position. This analysis uncovered small differences between full and reduced forms in the brief time interval where the forms differ. However, it is not obvious how GAMs can be used to tear apart processes that follow each other in time (or even partly overlap in time). Therefore, we took recourse to the overlapping time window approach described in Nijveld and Ernestus (2019). This approach is similar to the approach followed in Winsler et al. (2018), in which changes over time were investigated by means of `LME` analyses in nine non-overlapping time windows of 100 ms duration.

For modelling the EEG signals, we first downsampled the signals from 1 kHz to 100 Hz. Next, we shifted an analysis window along the time axis with a duration (analysis length) of 100 ms and with a step size of 50 ms through the signal. The left-hand border of the first window considered was at stimulus onset; the left-hand border of the last window was at 950 ms past stimulus onset. We align the output of `lme4` (Bates et al., 2015) models to the midpoint of the windows. In the analysis of the EEG data, we are especially interested in possible effects of the factors `reduction` and `cognate`. As in the analysis of the RT data, we limited the `lmer` analyses to the subset of the stimuli that received correct word/non-word responses.

Because the independent variables (sequences of amplitudes) in each window in each of the four analysis conditions are unique, it is impossible to determine a single model that is optimal for all windows in all conditions. For that reason, we decided to investigate models that are derived from the model that proved optimal for the analysis of the RT data. The models with onset on time-lock that we present here are optimised using the data in the time interval between 350 and 450 ms after the time-lock moment. With time-lock at stimulus *offset* we use the same model for the prestress and poststress conditions, with one exception. The local speed related predictor `BVis01` that appeared to have no impact in the RT analyses in the poststress condition was left out from the model for EEG analysis for that condition.

The best model we found with time-lock for the dependant variable at offset is:

```
lmer_offset = lmer(amplitude~trialindex2
+maRT+BVis01+
  I(time-startTime)+baseline+cognate* r-
eduction* RToffset* Freq* worddur+
  (1+Freq+worddur+RToffset|ppn)+(1|
item), data = segment, REML = T,
  control=lmerControl(optimizer="bo-
byqa",optCtrl=list(maxfun=100000)))
```

The reference level represents the values controls, full form, block 1 and post-stress. The above model estimates the amplitude of the EEG signal after syncing at stimulus offset. The optimal model for the data with time-lock at stimulus *onset* we found was very similar. The only difference is the replacement of the predictor `RToffset` by `RTonset`. The model reads:

```
lmer_onset = lmer(amplitude~trialindex2
+maRT+BVis01+
  I(time-startTime)+baseline+cognate* r-
eduction* RTonset* Freq* worddur+
  (1+Freq+worddur+RTcor|ppn)+(1|item),
data = segment, REML = F,
  control=lmerControl(optimizer="bo-
byqa",optCtrl=list(maxfun=100000)))
```

In all models, the level `full` is on the intercept for `reduction`; the level `control` is on the intercept for the factor `cognate`. Therefore, the coefficients for the factor `reduction` show the contribution of reduced items, over and above the baseline value; the coefficients of cognate items show the contribution of cognate status of an item, over and above the baseline value.

The models shown provide the best estimations in terms of AIC and have been compared against competing models with simpler and more complex fixed structure using REML=T. They all converge without singularities in the fixed or random structure. Addition of other predictors (such as trialindex2) to the random structure either led to divergent models or to higher AIC. The random structure was chosen such that the model converged, taking into account the recommendations in Bates et al. (2018).

In what follows, we will not discuss all predictors one-by-one, but instead focus on the differences between onset and offset model in terms of predictors of interest. Note that in the EEG models `RToffset` and `worddur` are on a linear scale, because there is no need to log-transform these measures for analysing EEG signals. `Freq` is used a shorthand for corpuslogFreq. Also note that both models contain a form of RT as a predictor that cannot be omitted without raising the AIC significantly. The fact that RT plays a role in the estimation of amplitudes (also directly after stimulus onset) suggests that these models implicitly show that RTs are the result of processes that accumulate evidence over time. Apparently, already in the earliest stages of the processing of a stimulus there are cognitive processes that affect EEG responses that in the end also affect the RT.

It is obvious that an analysis based on partially overlapping time windows incurs the "repeated tests" problem that plagues many methods for analysing ERPs. Since we are interested in the size and timing of the effects of factors that play out in competition with quite a number of confounding factors, we cannot take recourse to the cluster-based analysis popularised by Maris (2011) and Maris and Oostenveld (2007) (but see also the criticism of cluster-based significance testing in Sassenhagen & Draschkow, 2019). Rather, we will only consider an effect as potentially relevant if its *t*-value in the output of window-based `lmer` analyses exceeds the ±1.96 threshold in at least three subsequent windows. The requirement of three consecutive significant measures limits the risk of erroneously assigning significance by requiring that significance holds in a much larger time window.

To avoid being drowned in details, we decided to limit the presentation of the results of the `lmer` analysis to the two main factors of interest (`cognate` and reduction) and the interaction cognate: reduction. We are aware that the eventual effect of these factors is modulated by their interactions with other factors in the models. CorpuslogFreq is the only control factor that has been used in previous experiments; therefore, it might be possible to make predictions about its effect as a main factor. However, the role of frequency may change during the processing of a stimulus (e.g. Dahan et al., 2001), making predictions about its interaction with the two factors of interest quite difficult (e.g. Dahan et al., 2001).

The lmer models are "robust" in the sense that the results for the two focal factors and their interaction do not change significantly as a result of changing the interactions with and between the control variables. Therefore, we are confident that interpretations of the significance as a function of window position of the focal factors are valid and insight-lending.

3.4. Results of ERP analyses

EEG signals vary with time even if subjects are at rest. Therefore, the effects of exogenous stimulation and endogenous processing in EEG signals are defined as the difference with the signals at rest. For this reason, most EEG experiments follow a procedure that attempts to make sure that participants are in the "at rest condition" prior to the presentation of a stimulus. This allows assuming that the EEG signals in a short time interval (mostly 100 or 200 ms) before stimulus onset represent the "at rest" condition, so that the stimulus-related activity can be obtained by subtracting the average amplitude in the interval 100 or 200 ms preceding the stimulus from the signals recorded during processing the stimulus. This is the well-known baseline correction procedure.

However, when time-locking at the moment of stimulus *offset*, this reasoning clearly does not hold. Therefore, we decided to follow the procedure recently proposed by Alday (2019), in which the mean amplitude in a short time interval preceding the time-lock moment is used as an additional predictor in a regression model, instead of subtracting that value from all signal samples in the time interval following the time-lock moment. To keep the analyses of the onset and offset time-locks as similar as possible for the sake of comparison, we decided to also refrain from the conventional baseline correction with the time-lock on stimulus onset, and instead applied the procedure proposed by Alday (2019).

3.4.1. Time-lock on stimulus onset

Figure 5 summarises the results of the lmer analysis of the ERPs when time-lock is on stimulus onset. The top two panels show the predictions of model lmer_onset. To obtain these predictions, we pasted together the overlapping predictions in subsequent 100 ms analysis windows for all individual stimuli. The resulting traces were then smoothed by means of a zero-phase band pass filter with cut-off frequencies 0.1 and 25 Hz. Finally, the stimuli were averaged per stimulus type. The results are shown for the prestress and poststress conditions. The horizontal dashed line shows the position where amplitudes change sign (from positive to negative and vice versa). The lower panel shows the *t*-values for the factors cognate and reduction, and the interaction between these factors. The green and yellow dashed lines show the location of the values t=1.96 and t=−1.96, respectively. The blue markers show the results for the *prestress* condition; the red markers for the *poststress* condition. In all panels, *time*=0 corresponds to the onset of the stimulus word. The scales of the vertical axes are adapted to the values of the variables that are displayed. Note that we adhere to the convention of plotting ERPs with negative amplitudes upwards. The *t*-value plots have a standard *Y* -axis: positive values are upward. *t*-values outside the $\pm 1, 96$ bounds considered as significant are shown as asterisks. As said above, only sequences of at least three values $|T| > 1.96$ are considered as significant.

The *t*-values of the factors of interest represent the deviations from the average predictions (shown in the top panel) caused by the factors cognate and reduction, as well as the interaction cognate* reduction. Recall that the factor level full for reduction is on the intercept, and that the level control is on the intercept for the factor cognate.

It is interesting to compare the ERP predictions in the top panel of Figure 5 with the averages of the mTRF-corrected EEG signals in the right-hand column of Figure 3. The lmer models have removed a substantial part of the local differences between the averages of the raw traces of the four stimulus types, but while doing so, the overall shapes are pretty well preserved. Also note that the predictions (neither the raw and mTRF-corrected averages in Figure 3) show clear indications of the conventional N400. The P200 component that is clearly present in the poststress data in Figure 3 is substantially broadened and shifted in the predictions. Unsurprisingly, given the traces in Figure 3, a "late" P200 in the prestress condition is very weak, at best.

The factor cognate. From Figure 5, it can be seen that the factor cognate is significant in the poststress condition between 400 and 550 ms and between 650 and 850 ms after stimulus onset with negative *t*-values. Negative values imply that cognates add a negative increment to the intercept of the ERP estimate. Given

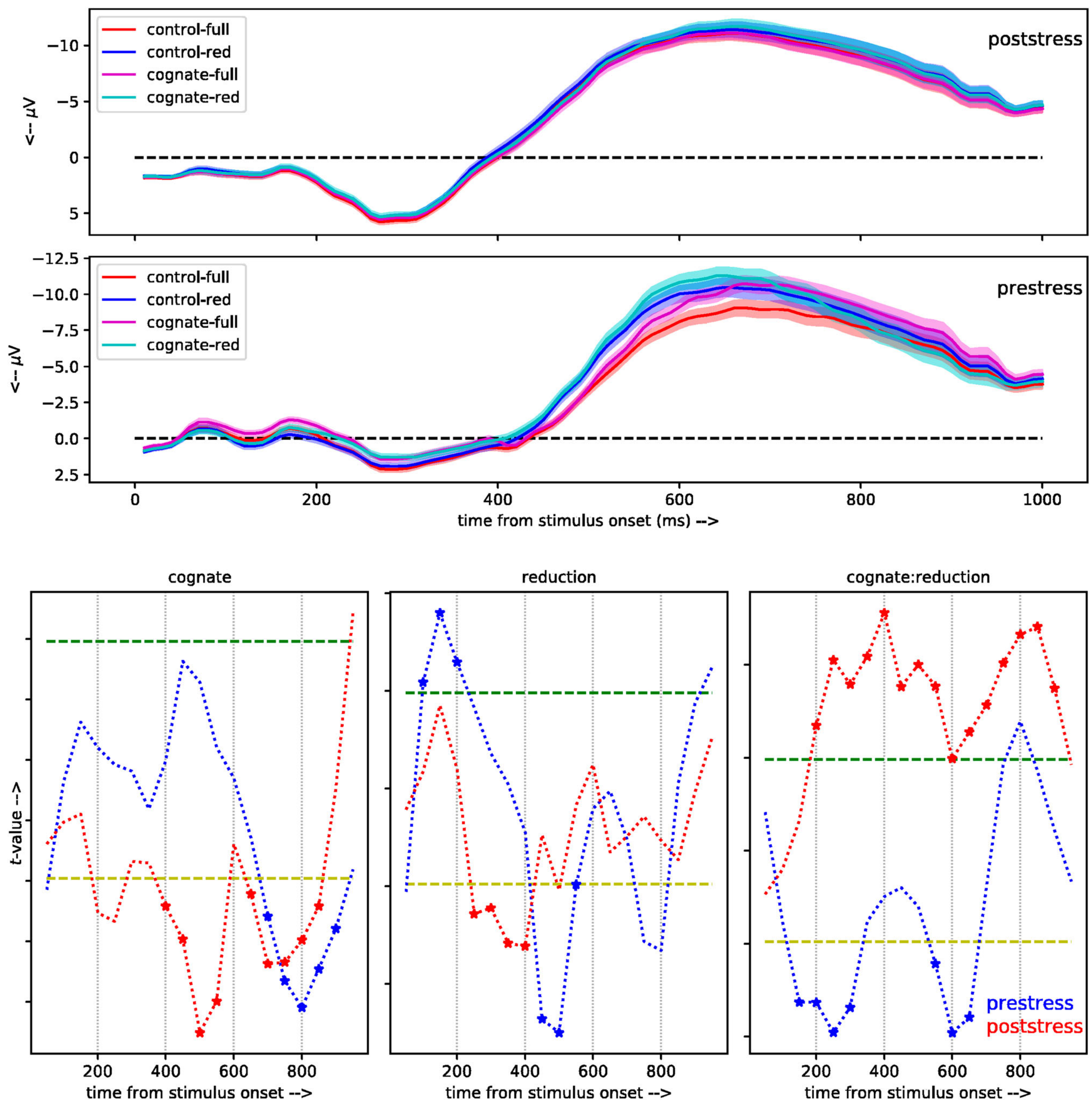


Figure 5. Results of the `lmer` analysis with time-lock on stimulus onset. Top: Predicted average traces (with standard error) of the of the four stimulus types. Bottom: *t*-values of `cognition` and `reduction` and their interaction. Red symbols: The results of the poststress conditions; blue symbols: the corresponding results in the prestress condition.

the fact that the average duration of the stimuli is close to 600 ms, this suggests that the cognate status of a stimulus word affects both phonetic form decoding and lexical-semantic access. The time window 400–550 ms of the cognate effect coincides with the time window of the N400 effect of cognate status reported by Midgley et al. (2011) and Peeters et al. (2013) in experiments with orthographic stimuli.

In the prestress condition the factor `cognate` is only significant – with a negative *t*-value – in the time interval between 700 and 950 ms after stimulus onset. This late effect suggests that the difference between cognates and control words makes no difference for phonetic form decoding, but that cognates do require extra processing effort in the time interval associated with lexical-semantic access.

The factor `reduction`. In the poststress condition, the factor `reduction` is significant, with negative *t*-value, in the time window 250–400 ms after stimulus onset. In the prestress condition, there is a significantly negative *t*-value (approximately 100ms later), in the time window from 450 to 550 ms. It is tempting to attribute both effects to a combination of phonetic form decoding and lexical access that affects reduced forms and that occurs later in the prestress condition. This interpretation is compatible with the idea that especially reduced prestress stimuli tend to yield a large number of viable candidates towards the end of the acoustic stimuli. Most probably, this leads to the activation of a large number of semantically unrelated words, which slows down access. Alternatively, listener might initially suspect that the reduced stimuli are pseudowords, and that backtracking to find a match with a real word is costly. Both, actually non-contradictory, interpretations are compatible with the inhibitory effect up to 200 ms after stimulus offset in the analysis with time-lock at stimulus offset.

In the prestress condition, the *t*-values for `reduction` have significant positive values in the time window between 50 and 200 ms. Due to the fact that the predictions in this time interval change sign from negative to positive twice in this interval, the effect is difficult to interpret.

The interaction between `cognate` *and* `reduction`. The interaction between `cognate` and `reduction` differs remarkably between the prestress and poststress conditions. A comparison of the patterns for the main factor `cognate` and the interaction `cognate:reduction` in the poststress condition suggests that reduced cognates diminish the negative increment associated with cognate as main factor. This effect is present in all time windows, starting at 200 ms after stimulus onset. Apparently, in the poststress condition cognate status mitigates the effects of reduction both during phonetic form decoding and lexical-semantic access. In the prestress condition, there is no such mitigating effect. If anything, reduced cognates add a negative increment to the baseline ERP in the time interval between 150 and 300 ms after stimulus onset, as well as in the time interval from 550 to 650 ms after onset.

3.4.2. Time-lock on stimulus offset

The results of model `lmer_offset` are summarised in Figure 6. The first thing that strikes the eye is that the effects of the two experimental factors are much more pronounced, compared to the results of model `lmer_onset`, especially in the time interval up to 500 ms after stimulus offset. It is also evident that the effects of the two factors differ substantially between the prestress and poststress conditions. This was to be expected from the traces in Figure 4.

The factor `cognate`. In the poststress condition, we see a positive increment being added in the time interval between 400 and 650 ms after stimulus offset. Note that the baseline value of the ERPs in that time interval is positive. There is no previous data about the relation between cognitive processing and ERP amplitude in this time interval. Here, we propose that this finding can be interpreted as a facilitatory effect (less effort needed) of L1–L2 co-activation at the semantic level.

In the prestress condition, the factor `cognate` adds a negative increment to the baseline ERP in the interval up to 450 ms after stimulus offset. The most plausible explanation for this observation is that phonetic form decoding of prestress stimuli takes more time, because distinctive phonetic information only starts becoming available at the second, stressed, syllable. However, there also might be a role of an interference between L1 and L2 lexical activations. This would imply that even in later stages of word processing co-activation is still possible, and can occur in a situation in which, initially, due to reduction, the phonetic form overlap is not enough to trigger co-activation.

The factor `reduction`. In the poststress condition, there is a significantly more negative ERP amplitude in the time interval between 200 and 350 ms after stimulus offset, arguably the time interval where phonetic form decoding gives way to lexical-semantic access, which may be more difficult because reduced forms match less well with canonical representations. There is a interval with significant negative *t*-values between 750 and 950 ms after stimulus offset. This effect is so late that it is most likely related to decision making. It might well be that making decisions about reduced stimuli requires more cognitive effort.

In the prestress condition the factor `reduction` adds a negative increment to the baseline ERP in the time interval up to 150 ms after stimulus offset. Most probably, this is associated with a combination of phonetic decoding and lexical-semantic access. `Reduction` adds a significant positive increment in the time interval between 550 and 700 ms after stimulus offset. This can only be related to lexical-semantic access and/or decision making.

The interaction between `cognate` *and* `reduction`. In the poststress condition, the significant *t*-values of the interaction are a mirror image of the significant effects of the factor `reduction`. This suggests that the factor `cognate` diminishes the effects of the factor `reduction`. In the prestress condition, on the other hand, `reduction` diminishes the effect of `cognate` in the time interval up to 450 ms.

3.4.3. Discussion of the ERP results

The analysis of ERPs with time-lock on stimulus onset and offset does not provide clear-cut answers to the

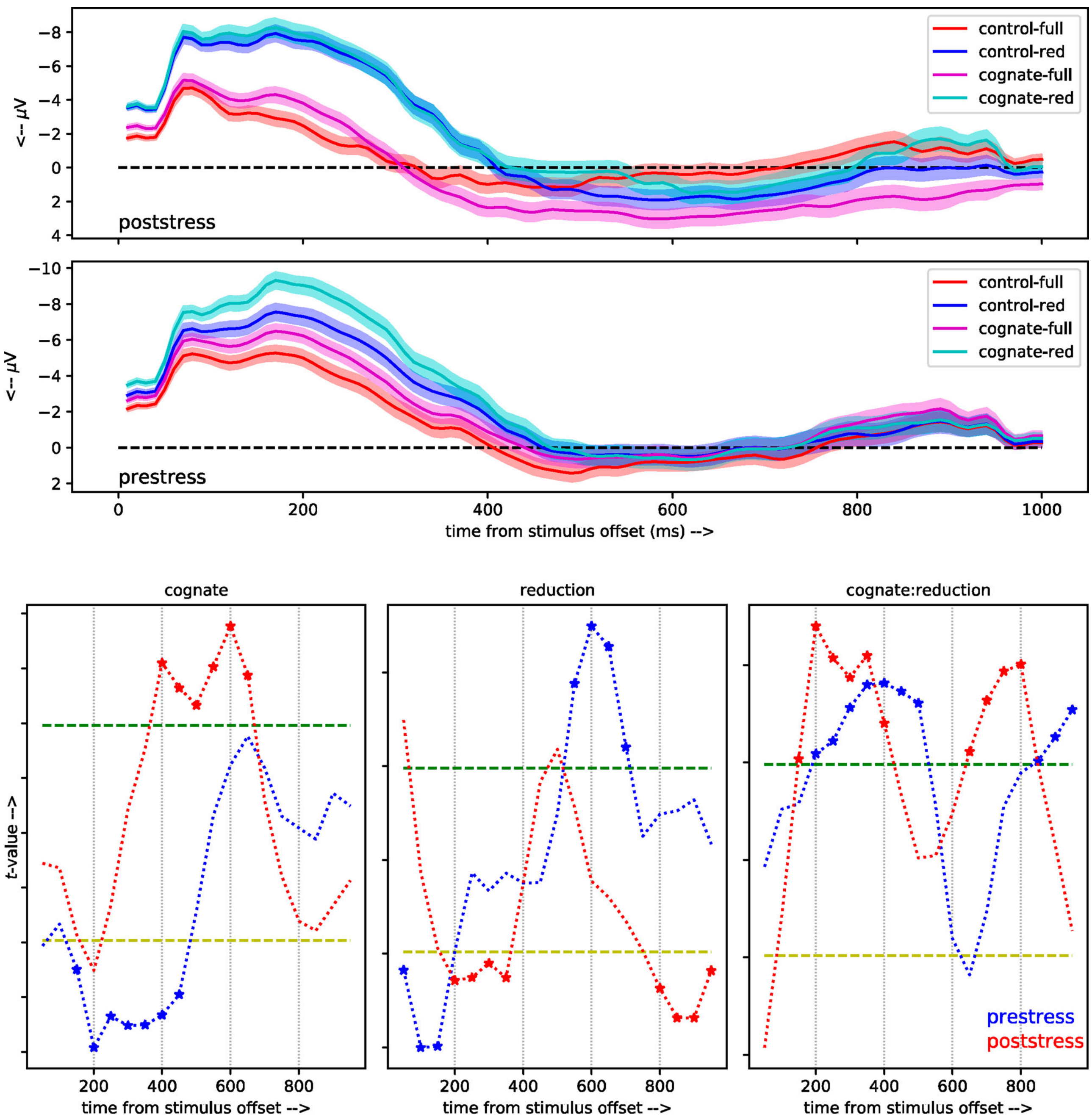


Figure 6. Results of the `lmer` analysis with time-lock on stimulus offset. Top: Predicted average traces (with standard error) of the of the four stimulus types. Bottom: *t*-values of `cognition` and `reduction` and their interaction. Red symbols: The results of the poststress conditions; blue symbols: the corresponding results in the prestress condition.

questions about the time course of cognitive processes and representations in the mental lexicon. We found that lexical frequency has a facilitatory effect shortly after the start of the acoustic stimuli and then again around the end of the stimuli (this effect is not shown in Figure 3). This appears to indicate that phonetic form decoding and lexical-semantic access are not completely independent processes. Still, it is interesting to investigate whether the bottom-up contribution of form decoding can be distinguished from the top-down contribution related to lexical-semantic access.

The cognate status of the stimuli has a significant effect during and after the course of the acoustic stimuli in the poststress condition. The effect takes the form of more negative amplitudes in the ERP. Perhaps, it reflects activation of both L1 and L2 representations at the same time, resulting in a larger number of active candidates and therefore in more negative ERP amplitudes, as per Barber et al. (2004). Mulder et al. (2013)

attribute a *less* negative ERP amplitude for words with a large morphological family to semantic co-activation. That we see *more* negative amplitudes implies that L1–L2 co-activation would then suggest that it is primarily based on phonetic form overlap. The fact that the inhibitory effect persists until 850 ms after stimulus onset casts doubt on the assumption that the overlap between L1 and L2 semantics should facilitate the processing of cognates. That the interaction `cognate:reduction` indicates less negative amplitudes in the same time intervals suggests that the extra activation is beneficial for reduced cognates. In turn, this suggests that the mental lexicon contains some representations of reduced pronunciations of words with a strong-weak pattern.

In the prestress condition, the negative-going effect of cognate status only occurs after the end of the acoustic stimuli. If the assumption that a larger negative ERP amplitude is a function of a larger number of active candidates is correct, there are two possible explanations (which are not mutually exclusive): the number of active candidates is increased because of the co-activation of L1 representations, or the number at stimulus offset is larger because more candidates are still active, due to the fact that the discriminatory information in the phonetic forms comes later in prestress stimuli. Both interpretations imply that there is L1–L2 co-activation before a link to semantic representations can be established. The mitigating effect that is present in about the same time interval in the interaction `cognate:red` with time-lock on stimulus offset does suggest an effect of L1–L2 co-activation. Therefore, semantic co-activation is likely to play a role, be it at a later time.

In the following we present data from the analysis of instantaneous power in several frequency bands, mainly with the goal to better distinguish between phonetic form decoding and lexical access. In addition, we investigate whether those analyses can shed additional light on the question about representations of reduced forms.

3.5. Analysis of oscillatory power in narrow frequency bands

The electrophysiological activity in the brain takes the form of complex waves that contain frequency components up to roughly 100 Hz. The overall shape of those waves is dominated by the lowest frequency components, due to the fact that the spectrum of the waves falls off steeply as a function of frequency. It is thanks to this low-frequency dominance that time-aligned averages of raw EEG signals provide useful indexes for effort of cognitive processes. However, during the last couple of decades it has become increasingly clear that the power in higher frequency bands of EEG signals provides information that may be linked to specific processes. This has resulted in a large number of papers that investigate those relations. Unsurprisingly, the results of these experiments do not always agree.

While EEG signals, and the ERPs that result from averaging those signals discussed in Section 3.4, alternate between positive and negative amplitudes, *power* is a (semi-) definite positive measure: it can only take positive values, and -exceptionally- become zero. The interpretation of power levels in narrow frequency bands in EEG signals is complicated by the fact that both enhanced and suppressed power levels have been related to cognitive activity. On the other hand, the interpretation of *t*-values is more straightforward: positive values are guaranteed to correspond to increasing power, while negative values correspond to decreasing power.

3.5.1. Oscillatory power representations that can be used in `lmer` analyses

To be able to link findings from individual frequency bands to the results of the statistical analysis of the ERPs, we created signal representations similar to the ERPs, which allow applying the exact same `lmer` analyses. For that purpose, we use the *instantaneous power* of the spectral components of EEG signals in the delta, theta, alpha and beta bands.[14]

The *instantaneous power* of a signal is computed as the (time varying) square of the absolute value of the Hilbert transform of that signals in a certain frequency band. We performed band pass filtering using zero-phase Butterworth filters. Similar to the previous ERP-based analyses, the resulting instantaneous power traces were time-locked at stimulus onset and on stimulus offset. No baseline correction was applied; as with the ERP we used the average power of individual traces in the 200 ms preceding the time-lock moment as an additional predictor in the `lmer` analysis.

Because there cannot be confusion about the interpretation of *t*-values in the analyses of instantaneous power, we opt for a representation that is different from the one used with the ERP data. Here, we combine the *t*-values of the two time-lock moments in a single figure (c.f., Figure 7). We show the *t*-values for the factors `cognate` and `reduction`, and the interaction between these factors. The top row (markers in cyan and magenta) shows the results in the poststress condition; the bottom row (markers in red and blue) contains the corresponding results in the prestress condition. The magenta and red markers apply to the time-lock on stimulus onset; the cyan and blue makers to time-lock on stimulus offset. This arrangement should help in understanding differences between the poststress and prestress conditions, as well as between the two time-lock moments. The horizontal axis in all panels shows the time from the time-lock moment. This allows us to show the results for the two time-lock choices in one panel. The left-most point is at 50 ms and the right-most point is at 950 ms after time-lock. The scales of the vertical axes are adapted to the *t*-values of the factor or interaction displayed. The top dashed horizontal line corresponds to t=1.96; the bottom dashed line to t=−1.96. As said above, only sequences of at least three values outside the ±1, 96 bounds are considered as of potential interest – these are shown as large dots. The *t*-values of the factors of interest represent the effects of those factors after the effects of the other predictors in the `lmer` analysis have been accounted for. Therefore, the represent the purest possible indication of the effect of the factors of interest.

3.5.2. Instantaneous power in the delta band

Harmony (2013) suggests that power increases of delta frequencies during mental tasks are associated with functional cortical deafferentation, or inhibition of the sensory afferences that interfere with internal concentration. According to Hunt et al. (2012), power in the delta band is associated to decision processes. Other authors associate oscillations in the delta (and in the theta) band to speech-specific processing in general (Di Liberto et al., 2015).

The results of the `lmer` analysis of the instantaneous power in the delta band are shown in Figure 7. Note that positive *t*-values along the *Y* -axis correspond with power enhancement relative to the baseline estimate, while negative values correspond to power suppression.

Time-lock on stimulus onset. Both in the poststress and prestress conditions, there is a significant decrease in delta power immediately after the start of the cognate stimuli. If Harmony (2013) is correct in associating delta power to regulating attention to exogenous activation, this would indicate that listeners paid more attention to the acoustic input for cognates than for control stimuli.

The significant power suppression for the reduced stimuli in the prestress condition during the first 250 ms of the acoustic stimuli corroborates the interpretation that there is extra attention paid to the acoustic input. In the poststress condition, there is a brief interval up to 150 ms after the start of the stimuli during which the stimuli have no "special" acoustic features, which makes this observation difficult to explain. In the time interval between 300 and 450 ms after stimulus onset, there is significant power suppression in the poststress condition; this interval roughly coincides with the second-weak-syllable. In the prestress condition, there is significant delta power suppression between 550 and 650 ms after stimulus onset. This is close to the end of the stimuli, and surely well beyond the time interval occupied by the starting -weak- syllable.

The significant *t*-values in the interaction `cognate:red` during the first 150 ms of the stimuli might mean that the effects of reduction during the same time interval are mitigated for the cognate stimuli. The increased delta power in the time interval between 300 and 500 ms in the poststress condition may be attributed to an increase in top-down activity that can be associated to both phonetic form decoding and lexical access. There is only an unconvincing hint at a similar effect for reduced cognates in the prestress condition, and if it would occur at all, it comes later than in the poststress condition. The fact that there is significant delta power suppression for reduced cognates from 750 ms onward in the prestress condition indicates that there is more to delta power modulation than regulating attention to exogenous activation.

Time-lock on stimulus offset. In the poststress condition, there is significant delta power suppression associated with cognate status in the time interval up to 350 ms after stimulus offset. In the prestress condition, there is no such effect. However, there is significant delta power suppression related to reduced stimuli, up to 400 ms (poststress) and 500 ms (prestress) after the end of the acoustic stimuli. The most probable interpretation of this effect is that it is associated with connecting acoustic-phonetic forms to the semantics of lexical entries. The delta power suppression in the case of reduced poststress stimuli starting at 800 ms after stimulus offset may be related to decision processes (cf., Hunt et al., 2012).

The significant power enhancement in the interaction `cognate:reduction` in the poststress condition, up to 300 ms after stimulus offset is best interpreted as a mitigating effect for reduced cognates, relative to the significant power suppression for the reduced stimuli in general. There is no corresponding mitigating effect for reduced prestress stimuli. In both conditions, there is significant delta power suppression between 450 and 700 ms in the poststress and between 600 and 800 ms in the prestress condition. This may mean that the decision procedure for reduced cognates requires a delta power suppression relative to the other stimulus types.

From our observations, it is not immediately clear how delta power suppression is linked to facilitation

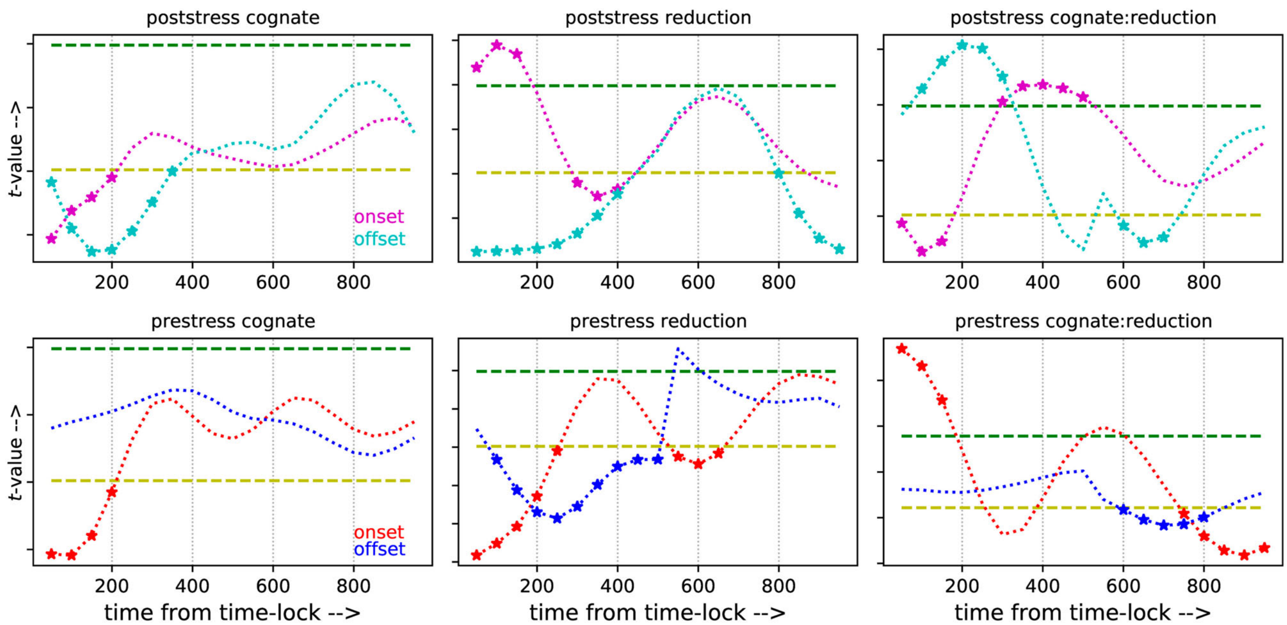


Figure 7. Results of the `lmer` analysis of instantaneous power traces in the delta band ($1 < f < 4$ Hz). Top row: Significance scores for the factors `cognate` and `reduction` and the interaction `cognate:reduction` in the poststress condition. Magenta: time-lock on stimulus onset. Cyan: Time-lock on stimulus offset. Bottom row: Corresponding significance scores in the prestress condition. Red: Time-lock on stimulus onset. Blue: Time-lock on offset. Analysis windows are centred at $n \times 50$ ms after stimulus onset. Green horizontal dashed line: t=1.95. Yellow: t=−1.95.

or inhibition of cognitive processes involved in spoken word recognition. Moreover, it is questionable whether power modulations in the delta band can help separate short-lived cognitive processes. A single cycle of the lowest frequency in the delta band (1 Hz) takes one second to complete, which is much longer than the duration of the large majority of the acoustic stimuli.

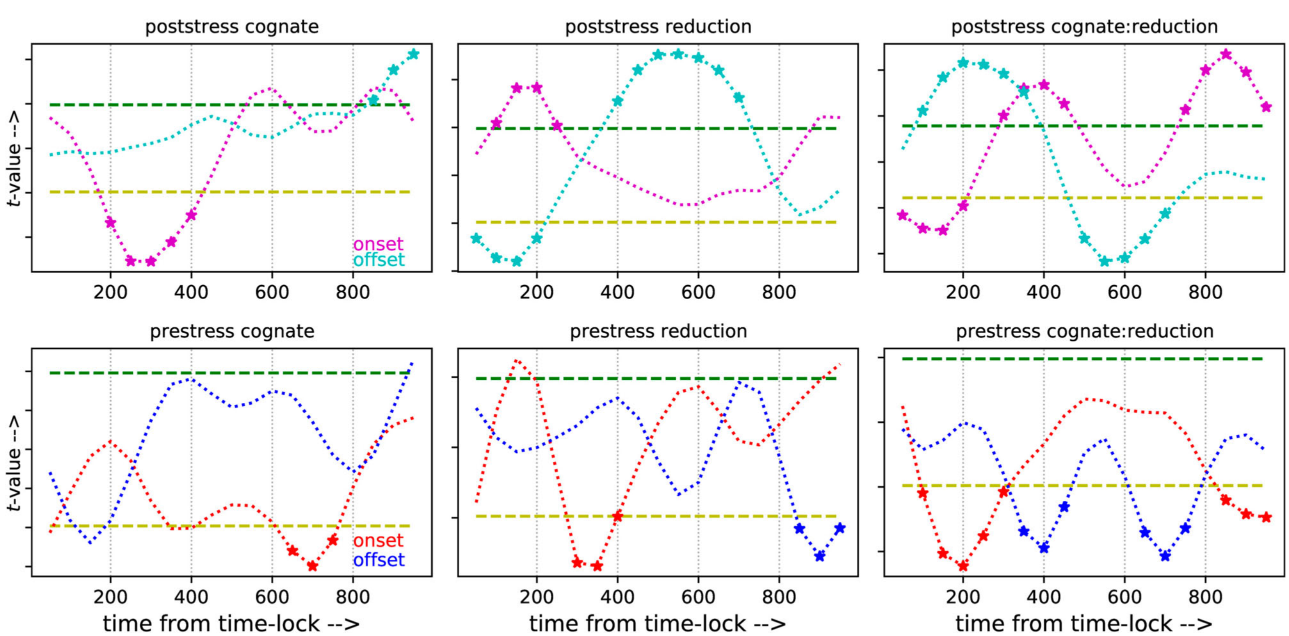


Figure 8. Results of the `lmer` analysis of instantaneous power traces in the theta band ($4 < f < 8$ Hz). Top row: Significance scores for the factors `cognate` and `reduction` and the interaction `cognate:reduction` in the poststress condition. Magenta: Time-lock on stimulus onset. Cyan: Time-lock on stimulus offset. Bottom row: Corresponding significance scores in the prestress condition. Red: Time-lock on stimulus onset. Blue: Time-lock on offset. Analysis windows are centred at $n \times 50$ ms after stimulus onset. Green horizontal dashed line: t=1.95. Yellow: t=−1.95.

3.5.3. Instantaneous power in the theta band

According to Luo and Poeppel (2007), acoustic-phonetic processing is related to phase synchronisation in the theta band (4–8 Hz), the modulation frequency band most important for speech intelligibility (Drullman et al., 1994). Recall that we analyse signals after mTRF correction, a process that removes most of the exogenous activation. Increased power of oscillations in the theta band has been associated with memory access, and specifically with the retrieval of lexical-semantic information (Bastiaansen et al., 2008).

The results of the `lmer` analyses of the instantaneous power traces in the theta band are shown in Figure 8.

Time-lock on stimulus onset. In the poststress condition, the factor `cognate` is associated with suppressed power in the theta band *decreases* in the time interval from 200 to 400 ms after stimulus onset. This suggests more attention to bottom-up form decoding for cognate stimuli during the first processing stage. However, in the prestress condition there is no power suppression during the unfolding of the acoustic stimuli. Instead, there is significant alpha power suppression for cognates in the prestress condition between 650 and 750 ms after stimulus onset. This is after the end of the acoustic stimuli for almost all reduced stimuli. Perhaps, this indicates increased activity that is needed for form decoding, before lexical-semantic access can be attempted.

For `reduction`, we found that the alpha power is higher during the first 250 ms of the stimuli in the poststress condition. This is surprising, because this interval coincides with the first, fully pronounced syllables. If the effect is indeed related to retrieval of lexical information, it is most likely restricted to phonetic form information. The significant suppression of theta power between 300 and 400 ms after stimulus onset in the prestress condition probably corresponds to extra effort devoted to phonetic form decoding.

In the first 200 ms after stimulus onset, we see a suppression of theta power in the interaction `cognate:red` in both the poststress and prestress conditions. This might suggest that there is some representation of the phonetic form of cognates, even if that cannot yet be used for semantic access. In the poststress condition, there is a significant increase in theta power between 300 and 450 ms after stimulus onset, which might be related to lexical-semantic access. In the prestress condition this advantage of reduced cognates does not occur. While there is significant increase of theta power in the time interval beyond 750 ms after onset in the poststress condition, there is a significant decrease in the prestress condition, from 800 ms after onset onward. This suggests a different role of semantics in processing reduced pronunciations of poststress (facilitatory) and prestress (inhibitory) reduced pronunciations of cognates.

Time-lock on stimulus offset. In the prestress condition, there is no effect of `cognate` in the theta band. In the poststress condition, there is a significant increase in theta power that starts at 850 ms after the end of the acoustic stimuli; this might indicate a rather late contribution of semantics in making a decision for poststress cognates.

In the poststress condition, the factor `reduction` is associated with theta power suppression during the first 200 ms after stimulus offset, and with theta power enhancement in the time interval between 400 and 700 ms after stimulus offset. This might indicate more effort devoted to form decoding immediately after the end of the stimuli, and more effort devoted to semantics later on. In the prestress condition, there is only a very late (beyond 850 ms after stimulus offset) suppression of theta power.

In the interaction `cognate:red`, there is significantly increased theta power in the time interval between 100 and 350 ms after stimulus offset in the poststress condition. This might indicate an extra contribution of semantics to the processing of reduced poststress cognates. A similar contribution does not occur in the prestress reduced cognates. There is significant suppression of theta power in the time interval between 500 and 700 ms after stimulus offset in the poststress condition, and between 650 and 750 ms in the prestress condition for the reduced cognates. The most likely explanation of these observations is an advantage for the reduced cognates in the decision process.

3.5.4. Instantaneous power in the alpha band

Suppression of the power of the oscillations in the alpha band ($8<f<12$ Hz) has been linked to ease of speech understanding (e.g. Strauß et al., 2014), attention (e.g. Wöstmann et al., 2019) and integration of contributions of separate brain regions (e.g. van Driel, 2015). In Palva and Palva (2007), alpha-suppression in a visual task is associated with visual attention, while alpha-enhancement is associated with internal computations. Drijvers et al. (2016) relate increases in alpha power to higher auditory cognitive load. This increased load was observed for reduced forms compared to full forms.

The results of the `lmer` analyses of power in the alpha band are shown in Figure 9.

Time-lock on stimulus onset. There is increased alpha power in the time interval 100–400 ms in the poststress condition and 200–400 ms in the prestress condition for the fact cognate. There is a similar increase in alpha power for the factor reduction in the prestress condition; in the poststress condition this effect comes later and is shorter-lived (between 450 and 500 ms). All these effects might be related to more effort spent to acoustic phonetic processing with cognates and with reduced forms. It is tempting to link this observation with the number of activated representations. If that is true, the fact that it also holds for reduced pronunciations suggests that the mental lexicon does contain reduced forms. In the poststress condition, the factor cognate is associated with a suppression of alpha power from 650 ms after stimulus onset onward; this may mean that cognates are easier to understand.

In the interaction cognate:red, there is a significant reduction of alpha power between 150 and 450 ms after stimulus onset in the prestress condition. The fact that the processing of reduced prestress cognates stands out is not surprising, but it is not easy to link the effect to the details of the phonetic form decoding process. In both conditions, there is a power suppression later on, in the poststress condition from 550 to 800 ms and in the prestress condition from 650 to 850 ms after stimulus onset.

Time-lock on stimulus offset. There is no effect whatsoever in the alpha power for the factor reduction in either condition. The same holds for the factor cognate in the prestress condition. However, in the poststress condition cognate status is associated with alpha power suppression in the first 250 ms after stimulus offset (probably the same as the suppression seen with time-lock on onset). This points towards a processing advantage for cognates over control stimuli, at the moment when the emphasis shifts from form decoding to lexical-semantic access. The suppression of alpha power in the interaction cognate:red for the prestress stimuli between 200 and 550 ms after stimulus offset might indicate extra attention spent in processing reduced cognates. In the poststress condition there is alpha power suppression between 650 and 800 ms after stimulus offset; in the prestress condition we see the opposite: alpha power increases between 750 and 850 ms after the end of the acoustic stimuli.

3.5.5. Instantaneous power in the beta band

According to Spitzer and Haegens (2017), oscillations in the beta band are implicated in top-down processing, long-range communication, and preservation of the current brain state, but also in endogenous information processing in working memory and decision making.

The results of the lmer analyses of the instantaneous power traces in the beta band are shown in Figure 10. Both time-lock points show wave-like results for all factors and interactions. Given the variety of cognitive processes with which power in the beta band has been associated, this may not come as a surprise. However, at this point we refrain from an attempts to interpret the significant effects.

3.6. Discussion of the EEG analyses

Perhaps the most important conclusion that can be made from the analyses of the instantaneous power traces in the delta, theta and alpha frequency bands is that there are multiple time windows where the effect of the factor cognate is significant. This holds especially for the cognates in the poststress condition, but there are several significant effects of cognate status present in the prestress condition as well. Moreover, significant effects of cognate status are found for both choices of time-lock moments. We also find significant effects of the factor reduction. In line with our expectation, the effects of reduction are more pronounced with time-lock on stimulus onset, especially in the prestress condition. While the effect of reduction was much stronger than the effect of cognate in the analysis of the behavioural data, that difference is absent in the EEG data. If anything, the effect of cognate is more pronounced. It may be that reduced pronunciations affect the processing chain differently in different stimuli (and/or in different participants). In terms of accuracy and RT those differences all have a similar effect. But when it comes to the actual underlying processes those differences can cause a substantial amount of smearing over time in the EEG responses.

In all four frequency bands, there are significant effects of the main factors cognate and reduction in the first 350 ms after stimulus onset. The interpretation of at least some of those effects in terms of general knowledge about modulation of power in specific frequency bands suggest that phonetic form decoding is not based exclusively on bottom-up processing of acoustic input. Thus there appears to be a contribution of top-down processing that can take place before semantic representations are activated.

The analysis of the ERPs yielded several indications that suggest that both L1 representations and representations of reduced pronunciation forms are activated (cf. Section 3.4.3). And this holds for both the poststress and prestress conditions. Therefore, our results do not corroborate the claim of, e.g. LoCasto and Connine (2002) and Bürki and Gaskell (2012) that words with a weak-strong patterns do not have reduced pronunciation forms in the mental lexicon. Admittedly, our conclusion that reduced forms are likely to exist in the mental lexicon

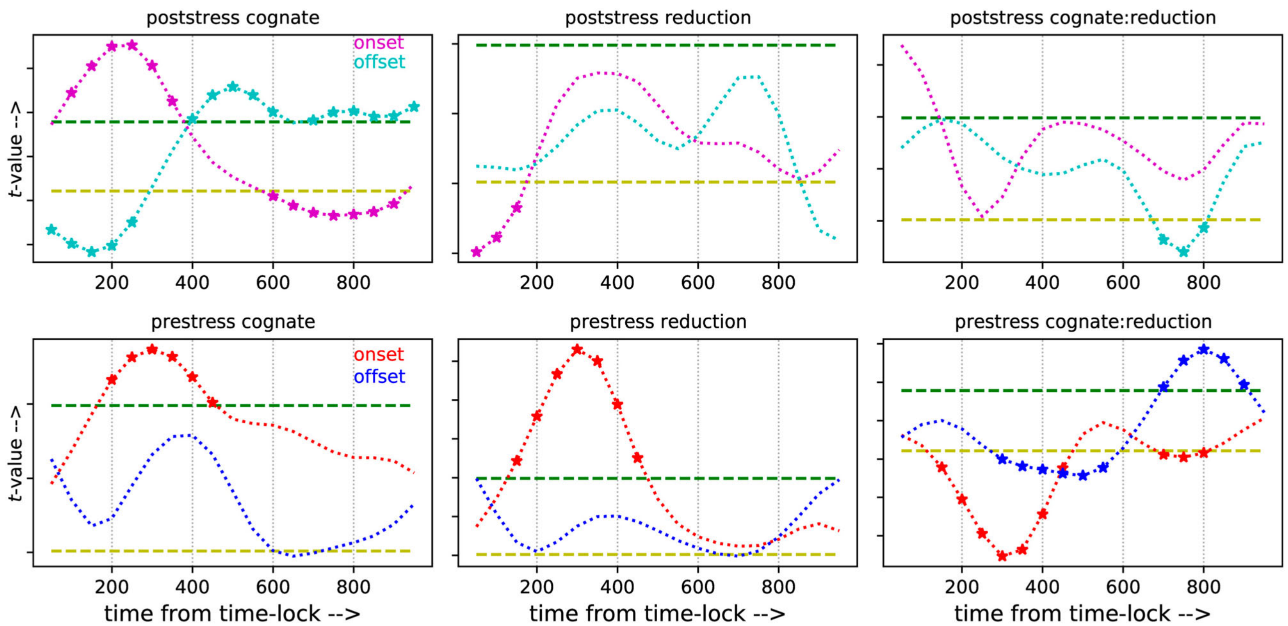


Figure 9. Results of the `lmer` analysis of instantaneous power traces in the alpha band ($8 < f < 12$ Hz). Top row: Significance scores for the factors `cognate` and `reduction` and the interaction `cognate:reduction` in the poststress condition. Magenta: Time-lock on stimulus onset. Cyan: Time-lock on stimulus offset. Bottom row: Corresponding significance scores in the prestress condition. Red: Time-lock on stimulus onset. Blue: Time-lock on offset. Analysis windows are centred at $n \times 50$ ms after stimulus onset. Green horizontal dashed line: $t = 1.95$. Yellow: t=-1.95.

is based on the claim of Barber et al. (2004) that processing effort is a function of the number of activated words (cf. 1.2 and 3.4.3). The alternative hypothesis is that increased processing effort for reduced forms is related to the reconstruction of the full pronunciation form. However, if that were the case, we would expect that effect to occur later, at a point in time when sufficient information is available to access possible full forms.

While we have seen effects that are most likely related to phonetic form decoding, we have also been forced to conclude that top-down processing starts immediately after the onset of the acoustic stimuli. The analyses of instantaneous power did not provide the information that would allow us to indicate the moment when semantic processing overtakes form decoding. On the contrary, we have seen several effects immediately after stimulus offset that can be attributed to both form decoding and semantic processing. Perhaps, it is not possible to escape the conclusion that form decoding and lexical-semantic access are fundamentally intertwined, so that clean separation of those processes is not possible.

Finally, we have seen hardly any effect that can be attributed to the decision process. Possibly, decision processes proper require yet another time-lock moment, namely the moment of button press. In ten Bosch et al. (2020), the authors investigated whether that third time-lock moment allows discriminating between correct and wrong decisions, and whether there is an effect of `cognate` and `reduction`. There were strong effects of factors such as logRT and maRT, especially for the pseudowords, but no effects for the factors of interest.

4. General discussion

In this study, we investigate the representation of reduced versions of content words in the mental lexicon by comparing the results of a lexical decision experiment in which advanced Dutch learners of English listened to full and reduced versions of English words. Half of the target stimuli are Dutch–English cognates, the other half are English words that have no form overlap with the Dutch translation equivalent. If the cognate status of a stimulus causes reduced versions of cognates to be judged more accurately and faster in an L2 lexical decision task than reduced non-cognates, it can be argued that the cognate status of a word is related to the status of its reduced representation in the mental lexicon.

Previous research (e.g. Bürki & Gaskell, 2012; LoCasto & Connine, 2002; Patterson et al., 2003) suggested that reduced representations in the mental lexicon are limited to words with a Strong–Weak (SW) stress pattern (poststress words), while words with a Weak–Strong (WS) stress pattern (prestress words) only have a representation for full forms. A special and interesting reason for comparing poststress and prestress words is the fact that Dutch listeners are highly familiar with heavily reduced forms of prestress words, be it mainly in past participle verb forms.

If cognates have an advantage over non-cognates in an L2 lexical decision task, this can be because the form overlap facilitates phonetic decoding, and/or because the meaning overlap facilitates lexical-semantic access. We use analysis of EEG signals to investigate whether the contributions of phonetic decoding and lexical-semantic access can be separated.

4.1. Behavioural measures

With respect to the accuracy scores, we found essentially the same results as Mulder et al. (2015) for the poststress data: non-natives responded more accurately to cognates than to non-cognates, but only when the cognate was presented in its full form. Apparently, reduced forms do not benefit from co-activation of native and non-native representations (while full forms do appear to benefit). Also, our data confirm previous findings (e.g. LoCasto & Connine, 2002) that recognising stimuli with a weak-strong stress pattern is more difficult than stimuli with a strong-weak pattern.

With respect to the effect of cognate status and reduction on RT measured at stimulus offset our results also confirm the findings in Mulder et al. (2015): cognate status as a main factor is not significant, but it mitigates the inhibitory effect of the interaction between stimulus duration and reduction. Reduction was not significant as a main factor either, but is shows a significant interactions with stimulus duration.

The results in the prestress condition are quite different, especially with respect to the factor `reduction`, which appears to be highly significant, both with RT`onset` and RT`offset`. However, here too `cognate` does not appear to be significant as a main factor.

There are substantial differences between the models for RT_{onset} and RT_{offset} (cf., Brand et al., 2021). More research is needed to understand whether simultaneous models of the two RT measures can help to untangle the contributions of several cognitive processes in making lexicality decisions.

We asked whether native speakers of Dutch, who are highly familiar with word forms that have a weak -and often heavily reduced- first syllable, followed by a strong second syllable would be more accurate and faster in judging English words with a heavily reduced weak initial syllable (i.e.prestress reduced words) compared to words with strong first syllable followed by a weak second syllable (i.e. poststress reduced words). Most of the frequent weak-strong forms in Dutch are past participle verb forms, which start with prefixes /bə, χə, vər/. It appears that familiarity with these derived native forms does not transfer to mono-morphemic forms in English. We argue that, rather, listeners had more difficulty in processing the reduced forms due to

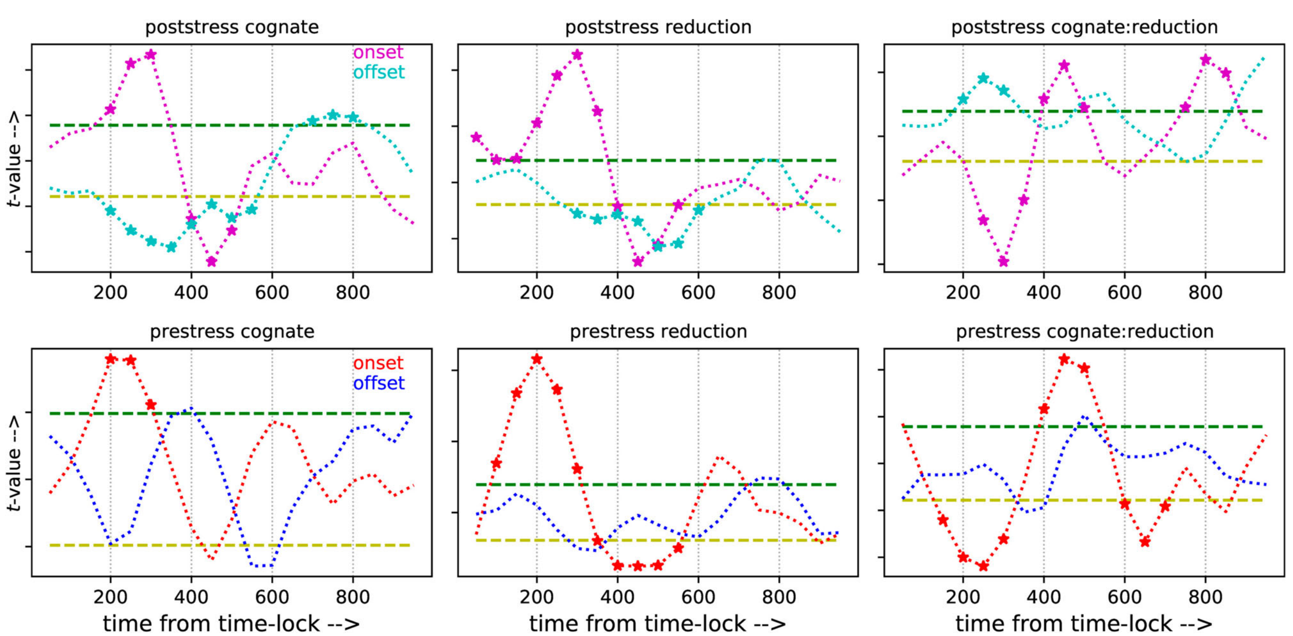


Figure 10. Results of the `lmer` analysis of instantaneous power traces in the beta band ($12 < f < 20$ Hz). Top row: Significance scores for the factors `cognate` and `reduction` and the interaction `cognate:reduction` in the poststress condition. Magenta: Time-lock on stimulus onset. Cyan: Time-lock on stimulus offset. Bottom row: Corresponding significance scores in the prestress condition. Red: Time-lock on stimulus onset. Blue: Time-lock on offset. Analysis windows are centred at $n \times 50$ ms after stimulus onset. Green horizontal dashed line: t=1.95. Yellow: t=−1.95.

the reduction affecting the beginning of the word, which turned the input into something uninterpretable until more word information became available (i.e. the number of word candidates that can match the first reduced syllable is simply too large).

Inevitably, the results of lexical decision experiments depend to a large extent on the stimuli, especially of the make-up of the non-word stimuli. This is especially relevant in auditory lexical decision, where each stimulus is a single sample from an infinitely large set of possible pronunciations. This holds for the full forms, and even more for the reduced forms.

Part of the problems the participants encountered with the reduced *prestress* items may have been due to the fact that such forms, frequent as they may be in connected discourse, may be somewhat awkward when spoken in isolation.

The frequency of occurrence of the words used as stimuli in psycholinguistic experiments almost invariably turns out to be a significant factor in explaining the results (e.g.Brysbaert et al., 2018; Dahan et al., 2001). In our experiment, the average word frequency of the stimuli was determined by the frequency of words that can be considered as cognates. From the information about the stimuli in Section 2.1.2 it can be seen that the average logFrequency values of the target stimuli are around 3.8. The average value in the `logFreqBNC (Zipf)` column in SUBTLEX-UK (the one we used in our models) is 2.08, with a range from 1 to 7.79. The fact that the averages in our selection are clearly to the right of the overall SUBTLEX-UK average shows that the target words were not concentrated in the low-frequency range. Therefore, we are confident that the target words did not incur a serious risk of biasing the overall patterns in our data towards some extreme that would limit the degree to which the results can be generalised.

4.2. EEG data

In auditory lexical decision, one can hypothesise at least three conceptually distinct processes, viz. phonetic form decoding, meaning recognition (semantic access) and decision making. There is substantial evidence that these processes operate at least partly simultaneously (e.g.Finkbeiner et al., 2014; Suri et al., 2020). Our interpretation of the effect of `logdur` on RTs measured from stimulus *offset* (see paragraph 2.3.2.3) adds to this evidence. Obviously, the simultaneity makes it very difficult, if not impossible, to unambiguously identify these processes and link them with specific features in EEG signals. Nevertheless, we have been able to extract information from the EEG signals that allows us to shed light on the way in which phonetic form decoding and lexical-semantic access are affected by full and reduced cognates, both in the poststress and prestress conditions. In addition, we have been able to extract information that is pertinent for the discussion about the existence of representations of reduced pronunciations in the mental lexicon.

To cope with the effects of a wide range of stimulus durations (in both conditions the duration of the longest stimulus was more than twice that of the shortest one), we combined analyses with time-lock on stimulus onset with analyses with time-lock on offset. This approach has the additional benefit that it makes it somewhat easier to separate processes related to phonetic form decoding from processes that are mainly related to lexical-semantic access. Still, it cannot be ruled out that phonetic form decoding continues for a short time after the offset of the acoustic stimuli, especially in the case of reduced forms in the prestress condition. At the same time, we have seen evidence of lexical-semantic access during the course of the longer stimuli. Although the physical reduction happens earlier in the prestress than in the poststress stimuli, we have seen a systematic delay of the EEG features in the prestress condition. This can only be explained by assuming that the recognition of reduced stimuli takes more time. In a model such as DIANA (Nenadić & Tucker, 2018; ten Bosch et al., 2015), this delay is easy to explain: the acoustically indistinct weak initial syllable activates a very large number of word candidates, from which a selection must be made on the basis of the information contained in the subsequent syllables.

Bürki and Gaskell (2012), following LoCasto and Connine (2002), interpret the fact that reduced poststress words yield similar priming effects as the full forms, while reduced prestress words do not, as a proof for the theory that the poststress words have two representations in the mental lexicon (one with, one without the /ə/), while the prestress words only have a representation that includes the /ə/. However, we have seen several effects in the EEG signals, especially in the analyses of the instantaneous power traces, that strongly suggest that both reduced poststress and prestress cognates can have representations in the mental lexicon. We have argued that these representations can take effect independently of the semantic load of the words. We assume that the process of lexical uncertainty reduction develops over time, as the acoustic stimuli unfold, in line with Bentum and Ernestus (2019). The co-activation of L1 and L2 representations can affect the recognition process in different ways in different stages. Early on, co-activation may increase the number of candidate words, while the shared meaning between L1 and L2 words may facilitate the processing once the form recognition has proceeded to a point where access to semantic representations is possible. Note that this line of reasoning can reconcile the seeming contradiction between Barber et al. (2004), who find that L1 and L2 co-activation leads to more negative ERP amplitudes because of a larger number of activated candidates on the one hand, and Mulder et al. (2013) on the other, who find that activating a larger number of closely related words has a facilitatory effect, in the form of less negative ERP amplitudes. The seeming contradiction is resolved by realising that the two effects are associated with different (temporal) stages of the recognition process.

4.3. Implications for future research

Recall that the `lmer` models for the analysis of the behavioural and the EEG data contained two predictors related to local speed effects (`maRT2` and `BVis01`). These predictors were not only highly significant in the models for the RT data (see Table 4); they also were consistently significant in virtually all windows in the EEG analyses. This finding calls into question the assumption that individual epochs in the EEG signals represent independent events and that all epochs are preceded by the exact same "resting state". It is quite likely that participants in a lexical decision experiment over the course of the experiment discover that there are about equal numbers of words and pseudowords, so that their expectations become biased by the number of preceding stimuli that are not a pseudoword. These expectations are impossible to avoid in conventional experimental designs. Therefore, there is a need for advanced statistical methods that can detect and mitigate the effects of local expectations.

In a similar vein, part of our `lmer` models, both for the behavioural measures and the EEG analysis, included factors such as `corpuslogFreq`, `worddur` and `RT` as random slopes under participants. Combined with the finding that the correlations of RT sequences of participants are quite low (and sometimes even not significant (c.f., ten Bosch et al., 2014, 2015), this strengthens the assumption that there can be substantial differences between participants in the way in which they perform the lexical decision task. Although this will make lexical decision (and other types of psycholinguistic experiments) more difficult and expensive, it would be worthwhile to include a much larger number of participants, so that it becomes possible to find clusters of participants that seem to approach the task in similar ways.

In this paper we limited ourselves to analysing the signal from the central censor `Cz`. The major argument for this decision is that the spacial resolution of EEG signals is rather low. We checked that a one-way ANOVA analysis almost always indicated potentially relevant differences between and within conditions in a large number of sensors, located at different scalp positions. Having said this, we must acknowledge the increasing number of studies that attempt to link neural activity that is presumed to be associated with specific cognitive processes to specific brain regions. If it were possible to link, for example, phonetic form decoding to one brain area and lexical-semantic access to another, then it would surely become easier to separate these processes. However, it is unlikely that such brain areas can be convincingly identified by means of EEG recordings. Even with MEG recordings, which have a much better spatial resolution, it might prove difficult to identify brain areas that can unambiguously linked with specific cognitive processes, such as phonetic form decoding. Quite likely, that process will involve more brain areas (or brain functions) than the auditory cortex.

Like almost all other studies of lexical decision we limited our research to an analysis of behavioural and EEG data related to correctly judged target stimuli. In doing so, we ignored about half of the items in our data set, viz. the pseudowords. If the pseudowords can be grouped, for example according to the position of the first phone that makes the stimulus a non-real word, or according to the type of violation, the data would be amenable to the same type of statistical analysis that we used with the target stimuli. Such an analysis could add important information to theories about the relation between phonetic form decoding and lexical access.

While DIANA (ten Bosch et al., 2014) as a model of auditory word recognition can explain most of the findings from the analysis of the EEG data, there is one intriguing issue where DIANA might need to be adapted. In DIANA, there is only one concept of lexical frequency that, in a Bayesian way, affects the activation of word candidates, by using priors. The finding that acoustic-phonetic representations affect phonetic form decoding without a contribution of the meaning of the attendant word(s) raises the question whether DIANA should rather apply syllable frequencies in its Activation component, and leave the impact of lexical frequency to the Decision component.

Papers such as ten Bosch et al. (2014), Arnold et al. (2017) and Magnuson et al. (2020) have shown that the assumption about the absolute *necessity* of a categorical (segmental) pre-lexical representation, as taken for granted in models such as TRACE (McClelland & Elman, 1986) or Shortlist (Norris & McQueen, 2008), is not warranted and potentially harmful. Although Magnuson et al. (2020) cannot be interpreted as an ecologically plausible model, for example due to the use of synthesised audio during training and test, models that make use of end-to-end modelling of the form-meaning mapping show that the cognitive route *may* sidestep the prelexical and even the lexical layers. The finding that acoustic–phonetic representations can affect spoken word processing without a direct link to semantic representations points towards a new type of model (and theory) in which pre-semantic (acoustic) representations form a gateway to semantic representations, and, if needed for a specific task, spelling and phonemic forms. As a consequence, in such a theory the need for a sharp distinction between full and reduced pronunciations is limited and possibly absent.

5. Conclusion

In this study, we use the cognate status of half of the target stimuli in an L2 lexical decision experiment to investigate the representation of reduced forms in the mental lexicon for words with Strong–Weak and Weak–Strong stress patterns. We analyse the conventional behavioural measures *accuracy* and *reaction time*, as well as EEG signals recorded during the experiment.

Thanks to a comparison of RT_{onset} and RT_{offset} the behavioural data yielded indirect indications for the existence and role of reduced form representations. The comparison of cognates and non-cognates, as well as full and reduced stimuli in the analysis of the EEG signals uncovered indications for a role of phonetic form representations in the processing of reduced forms. Although we find statistically significant effects of both cognate status and reduction during the complete time interval from the start of the stimuli to the moment when the decision is expressed, it is not possible to unambiguously relate significant effects in the EEG data to specific cognitive processes that are supposed to be involved in spoken word recognition. For such an assignment, we need a theory of spoken word recognition and a corresponding computational model that account for more detail of the time course of putative cognitive processes than the most elaborate existing models. The results of this study show ways for elaborating existing theories and models especially focussing on differentiating early and late bottom-up processes, phonetic decoding and top-down semantic processes.

Notes

1. http://www.speech.cs.cmu.edu/cgi-bin/cmudict
2. We used the data in the column "logFreqBNC(Zipf)".
3. https://www.neurobs.com/
4. The figure is produced using the function `plot (allEffects(modelname))` in the R package `effects`.
5. A Python implementation of the procedure is included in the Supplementary Material.
6. Procedures for computing `maRT` and `BVis01` written in R are included in the Supplementary Material.
7. Recall that model `RT.onset.poststress` does not include interactions between `cognate` and `reduction`.
8. This was checked by a `ranef` analysis. This analysis did not yield suspect stimuli. Therefore it seems that different participants were startled by different stimuli.
9. https://www.brainproducts.com/index.php
10. The only exception was in the analysis of instantaneous power in the low gamma band, for which we used a low-pass filter with a cut-off frequency at 45 Hz.
11. Target stimuli are limited to cognate and control stimuli in *poststress* and *prestress* conditions.
12. The same is true for representation of the signals in separate frequency bands.
13. For ease of reading, we omit the *mTRF*-correction in the remainder of the text.
14. The instantaneous power as a function of time is equivalent to the color-coded power in that band in the conventional time-frequency spectra.

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