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On the flexibility of the sound-to-meaning mapping when listening to native and foreign-accented speech

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ABSTRACT

Extracting linguistic information from the speech signal is critical to successfully communicate with others. We usually carry out this sound-to-meaning mapping easily, but this process may be hampered under adverse listening conditions. Thus, exploring whether foreign accents might affect the sound-to-meaning mapping is particularly relevant, as interactions with these speakers are increasingly common in the globalized world. In this study, we conducted a cross-modal priming task, in which participants ($N = 24$) were presented with auditory primes uttered by a native or by a French foreign-accented speaker of Spanish, and with visual targets that had different degrees of relatedness to the prime: repeated, semantically related, or unrelated words. Behavioral and EEG measures were analyzed, and we found a significant relatedness effect (i.e., a processing advantage for repeated compared to related words, and for the latter compared to unrelated words). However, speakers' accents had no effect on the results. To further explore the potential effect of speakers' accent on the sound-to-meaning mapping, we conducted a second study, in which participants ($N = 22$) were presented with the same task, although in this case primes were uttered by the same native speaker as in the previous experiment, and by a German foreign-accented speaker with a stronger accent. We replicated the results observed in the first study. Taken together, our results show moderate evidence that speakers' accent does not affect the sound-to-meaning mapping, suggesting that this is a robust and flexible process that is not compromised by auditory variables related to speakers' characteristics.

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1. Introduction

Understanding another person's speech requires mapping the auditory input to stored lexical and semantic representations. The human brain can perform this sound-to-meaning mapping very fast: acoustic information travels from the cochlea to the primary auditory cortex in approximately 15–20 msec, and the earliest word access and recognition processes occur rapidly thereafter, only 50 msec after the presentation of the acoustic information needed for word identification (MacGregor et al., 2012). Nevertheless, there are several potential challenges (not mutually exclusive) in accomplishing this task: external factors (such as noise, which can affect the comprehensibility and/or intelligibility of the acoustic signal), linguistic factors (such as phonetic or lexical/semantic ambiguity), listener-related factors (such as hearing problems, difficulties in accessing the mental lexicon, or unfamiliarity with the speaker's accent or other indexical properties), and speaker-related factors (such as difficulties in speech production, or the use of nonstandard accents). We will focus on the latter point, i.e., whether the speech produced by speakers with a nonstandard accent may affect the sound-to-meaning mapping.

This is an issue of great relevance, as interactions with nonstandard-accented speakers are becoming more and more frequent in the globalized world. For instance, on January 1, 2020, there were 23 million people with citizenship of a non-member country (5.1% of the population), and 13.4 million persons with the citizenship of another member state (2.97% of the population), residing in European Union countries (Eurostat, 2021). Importantly, most of these people were not native speakers of the official languages of the countries they moved to (or, if they were native speakers, they spoke a different regional variant), which means that in many cases they would speak with a foreign accent. As we explain below, up to this point the literature on how foreign-accented speech affects the sound-to-meaning mapping is highly contradictory. But before addressing that issue, we need to elaborate on the different mechanisms proposed to explain the sound-to-meaning mapping.

1.1. *Theoretical perspectives on the sound-to-meaning mapping*

Traditional models of speech recognition (e.g., TRACE, McClelland & Elman, 1986; cohort, Marslen-Wilson, 1987; or neighborhood activation models, Luce & Pisoni, 1998) typically assume that the mapping of sound to meaning follows a rather serial sequence: acoustic representations are the first to be incorporated, followed by phonetic, and finally lexical, semantic, or syntactic representations. Although the activation of some of these representations may occur in parallel and interact with each other, there would be a single computational pathway in the brain from sound processing to the activation of the meaning of words. Under these models, a mismatch between the speakers' utterances and listeners' representations (due to the acoustic-phonetic variability introduced by foreign accents, as in the case we are interested in here), may affect the processing and incorporation of the first acoustic and phonetic representations, and consequently hinder and/or delay the activation of lexical and semantic representations (although top-down mechanisms could counteract these difficulties, at least partially; e.g., Goslin et al., 2012).

However, more recent perspectives on the organization of speech processing suggest that the sound-to-meaning mapping may not be such a sequential process. For example, the dual-stream model of speech processing argues that there are two distinct and parallel pathways in the brain: a dorsal pathway more directly related to the online sequencing of speech sounds and the interaction between phonological and motor representations, and a ventral pathway that would be responsible for mapping acoustic and phonological representations to lexical-semantic representations (Hickok & Poeppel, 2007). Thus, while perceptual variation could be solved by the dorsal pathway (e.g., in the inferior frontal cortex; Rauschecker & Scott, 2009), relatively independent and automatic semantic processes may be occurring in the ventral pathway (e.g., in the left anterior superior temporal gyrus; Lau et al., 2013, 2016). Similarly, other studies have shown that the speech signal activates lexical items from the earliest processing stages, without waiting for phonological categories to be disambiguated. More concretely, lexical hypotheses would be activated from the earliest stages of word comprehension, based on the limited bottom-up acoustic evidence available, and phonological disambiguation would occur later, so it does not act as a bottleneck in lexical activation; also, lexical frequency or semantic constraints might reduce the size of the cohort of lexical hypotheses, rendering less predictive power to phonological details in the processing system (Gwilliams, Poeppel, et al., 2018). Under these less sequential perspectives, foreign-accented speech would not necessarily hinder access to lexical-semantic representations, because the acoustic variability introduced into the input by the foreign accent would to some extent be treated independently of lexical-semantic processing.

1.2. *Processing of foreign-accented speech*

Nevertheless, as mentioned above, it is still unclear whether foreign-accented speech affects the sound-to-meaning mapping. On the one hand, behavioral studies have shown that native listeners of a language adapt very quickly to foreign-accented speech (e.g., Bradlow & Bent, 2008; Clarke, 2000). In fact, adaptation to foreign-accented speech can occur during the first minute of exposure. While during the first moments of exposure listeners respond faster to whether visual probe words were presented in auditory sentences produced by native versus foreign-accented speakers, this difference disappears within the first minute of exposure (Clarke & Garrett, 2004). These results emphasize the flexibility of listeners' lexical recognition processes when listening to foreign-accented speech. As for the semantic processing of foreign-accented speech, behavioral studies are scarce, and have often taken an indirect approach. For instance, when presented with the DRM paradigm (in which participants typically falsely remember unstudied words semantically associated with the word lists they studied), listeners present lower false recognition rates for word lists presented in a foreign versus native accent (Romero-Rivas et al., 2019). This result might suggest that foreign-accented speech causes a reduction in the activation of semantic information, but alternative explanations (e.g., the distinctiveness of foreign-accented speech may trigger a more careful processing strategy, reducing false recognition rates) could account for it. Therefore, more behavioral evidence is needed to conclude whether foreign-accented speech affects the sound-to-meaning mapping or not.

On the other hand, the bulk of the research on lexical-semantic processing during foreign-accented speech comprehension has been carried out with electroencephalographic (EEG) recordings. Most of these studies have focused on exploring the modulation of the N400 event-related potential (ERP) component when listeners hear sentences spoken by native versus foreign-accented speakers. The N400 usually appears roughly between 300 and 500 msec after word onset, with a centro-parietal distribution, and it is sensitive to the well-formedness and semantic expectations generated during sentence comprehension (see Kutas & Federmeier, 2011, for a review). And research using the N400 component as an index of lexical-semantic processing during the comprehension of sentences produced by native and foreign-accented speakers has found very contradictory results.

First, only a few studies have directly explored the processing of regular sentences produced by native and foreign-accented speakers. A study found lower N400 amplitudes for sentences' final words when these were produced by foreign-accented versus native speakers, suggesting that top-down mechanisms were put into play when listening to foreign-accented speech in order to counteract the phonetic variability that could not be normalized in earlier linguistic processes (Goslin et al., 2012). However, another study found more negative N400 amplitudes for words embedded in sentences uttered by foreign-accented versus native speakers, but only during the first moments of exposure, pointing out that lexical-semantic processing of foreign-accented speech improves after brief exposure (Romero-Rivas et al., 2015).

Furthermore, other studies that have investigated the lexical-semantic processing of foreign-accented speech by using semantic violations paradigms (e.g., ‘When my niece sleeps in my apartment, I always read her a *book/bread* at night’) or manipulations of lexical expectancy (e.g., ‘He never scores goals, he is an awful *soccer/handball/videogames* player’), have also found very contradictory findings. Some observed more negative N400 effects during critical words processing when sentences were spoken by foreign-accented versus native speakers (Romero-Rivas et al., 2015, 2016). Others found delayed or more time-dilated N400 effects when listeners heard foreign-accented versus native speech (Grey & van Hell, 2017; Grey et al., 2020; Gosselin et al., 2021). A third group of studies has found no overall differences between the N400 effects generated by foreign-accented and native speech (Hanulíková et al., 2012; Holt et al., 2018; Foucart et al., 2020), even though in some cases they reported differences in the topographical distributions (Hanulíková et al., 2012) or time clusters (Holt et al., 2018) of the N400 effect across accent conditions. And, finally, another study observed larger N400 effects for semantic violations due to slips of the tongue when they were produced by native versus foreign-accented speech (Xu et al., 2020).

Although some explanations have emerged attempting to solve this disparity of results (e.g., listeners' familiarity with the foreign accents presented, Grey & van Hell, 2017; or listeners' characteristics, Holt et al., 2018), what seems to be clear is that the variability of analysis parameters used throughout these studies could have affected the results obtained. This last explanation proved to be right (although this does not rule out the potential effects of listeners' familiarity with foreign accents, or of the characteristics of the listeners, on the comprehension of foreign-accented speech): by applying different analysis criteria to stimuli like those presented in the previous studies, the results change dramatically (Strauber et al., 2021). In addition, one of the fundamental characteristics of foreign-accented speech is that word duration is longer than when lexical items are produced by native speakers (e.g., Romero-Rivas et al., 2015), which in turn may result in a later appearance of the point of auditory uniqueness (i.e., the first point in the acoustic signal where a unique lexical candidate can be recognized) when listening to foreign-accented versus native speakers. This could be critical, since manipulating the point of auditory uniqueness can cause the N400 effect to appear earlier or later, or to have a greater or lesser amplitude (e.g., O'Rourke & Holcomb, 2002). Thus, although using auditory stimuli produced by foreign-accented and native speakers is undoubtedly the most ecologically valid approach, it could be causing uncontrolled alterations in the EEG recordings, and potentially modulating the results. Due to all of the above, in the present study we will use several approaches for analyzing the EEG data, and explore lexical-semantic processing of foreign-accented speech by using visual stimuli.

1.3. *The present study*

To summarize, in this study we aim to clarify whether foreign-accented speech hinders the sound-to-meaning mapping or not. To explore this, we presented participants with a cross-modal priming task, in which primes were presented aurally and produced either by a native or by a French foreign-accented speaker of Spanish. Targets were presented visually on the computer screen (the same word as the prime *repeated* cross-modally, a semantically *related* word, an *unrelated* word, or a non-word). Participants' task was to respond as fast and accurately as possible whether the visual targets were real words or not (lexical decision task), while we recorded their EEG activity. This single-word cross-modal priming task has been used extensively in studies utilizing ERPs to explore lexical-semantic processes (e.g., Holcomb & Anderson, 1993), but so far it has not been used in the scientific literature exploring lexical-semantic processing of foreign-accented speech by means of neural measures. Critically, it will allow us to overcome some of the limitations present in previous studies, as discussed above (i.e., potential differences in the points of auditory uniqueness between words produced by native and foreign-accented speakers).

We had two opposing hypotheses:

- On the one hand, if the acoustic-phonetic variability introduced by foreign-accented speech hinders the lexical-semantic processing of auditory primes, this should negatively affect the lexical-semantic processing of *repeated* and *related* targets. This result would support the literature that has found significant differences in lexical-semantic processing between native and foreign-accented speech comprehension (e.g., Gosselin et al., 2021; Grey et al., 2020; Grey & van Hell, 2017; Romero-Rivas et al., 2016, 2015). Also, it would support the more traditional speech recognition models (e.g., TRACE, McClelland & Elman, 1986).
- On the other hand, if variability in the acoustic signal is treated relatively independently of access to lexical-semantic representations (e.g., Hickok & Poeppel, 2007; Gwilliams, Poeppel, et al., 2018), foreign-accented primes might not hinder targets processing. This result would support previous investigations that have found no overall differences in lexical-semantic processing between native and foreign-accented speech comprehension (Hanulíková et al., 2012; Holt et al., 2018; Foucart et al., 2020).

2. Method

2.1. *Participants*

Based on the sample size of previous studies that explored lexical-semantic processing during the comprehension of foreign-accented speech (e.g., Goslin et al., 2012; Hanulíková et al., 2012; Romero-Rivas et al., 2015, 2016), 24 participants (15 women, mean age = 23.48; range = 18–32 years) were recruited from the Center for Brain and Cognition (University Pompeu Fabra) database. They partook in the experiment in return for monetary compensation (10 €/h). All were native speakers of Spanish, right handed, and had normal or corrected to normal visual and hearing acuity. EEG data from one participant were removed, since data were corrupted.

Research was approved by the Academic Board of the Universitat Pompeu Fabra, and the experiment was conducted according to the principles expressed in the Declaration of Helsinki. In addition, written informed consent was obtained from all participants.

2.2. *Materials*

Auditory primes were 270 Spanish words (all containing the phoneme/r/, which is particularly difficult to produce for some foreign speakers of Spanish; McBride, 2015), recorded by the Spanish native speaker and the French foreign-accented speaker of Spanish. We used a sound card running at 44.1 Hz sampling rate for the recordings, with 32 bits resolution. The foreign-accented speaker was presented with samples uttered by the native speaker before recording the words, to minimize differences in speech rate and prosody. Audio tracks were normalized in terms of intensity using the software Audacity®.

Visually presented targets were the same words as the primes *repeated* cross-modally, semantically *related* words (we used the first associates from the free association norms in Spanish; Fernández et al., 2003; the full list is available in the Supplementary materials), *unrelated* words (taken from the same pool of words as the cross-modally repeated words, counterbalancing their presentation between participants; see Design), or non-words.

Accent strength of the native and foreign-accented speakers was rated by a sample of participants (N = 22) who did not take part in the main experiment. These participants were also native speakers of Spanish, selected from the same participant pool. Each participant listened to 20 words spoken by the native Spanish speaker, and 20 words spoken by the French foreign-accented speaker (in such a way that each auditory prime was at least listened by two participants). They had to rate the accent of each word from 1 (native speech) to 5 (very strong foreign accent). Listeners rated the Spanish native speaker as native (1.05 out of 5), and the French foreign-accented speaker as having a mild accent (2.87 out of 5; t(1,21) = 14.23; $p < .001$).

Intelligibility of the speakers was rated by another set of participants (N = 9), who did not take part in the main experiment. Participants recognized (i.e., correctly transcribed) 100% of the words spoken by the native speaker, and 98% of the French-accented words (the words that were not recognized varied between participants). This was overall a very good performance, and the intelligibility ratings of the native and French foreign-accented speakers were not significantly different (t(1,8) = 1.54; $p = .08$).

2.3. *Design*

Participants had to complete a lexical decision task. They listened to 270 primes, of which 180 primed the experimental written targets (60 primed cross-modally *repeated* words, 60 primed semantically *related* words, and 60 primed *unrelated* words). For each prime-target experimental condition, 30 primes were spoken by the native speaker, and 30 primes were spoken by the foreign-accented speaker. The remaining 90 auditory primes (45 spoken by the native speaker, and 45 by the foreign-accented speaker) were followed by non-words phonologically plausible in Spanish. We counterbalanced the speaker (native, foreign-accented) and the relationship between primes and targets (*repeated*, *related*, *unrelated*) across participants, creating a total of 6 experimental lists.

Hence, we used a within-subjects design, with primes' *accent* (native, foreign-accented) and primes-targets *relatedness* (repeated, related, unrelated) as independent variables. For behavioral results, we had accuracy and response times to written targets as the dependent variables; importantly, for the analysis of response times we excluded incorrect responses and response times above or below 2.5 SD of the mean for each target condition and participant. For electrophysiological measures, we used the amplitude of the N400 component as dependent variable (see “EEG recordings, preprocessing and analyses” for more details).

2.4. *Procedure*

Participants were tested individually in a sound-attenuated room. They were instructed in the task but no information about the accent manipulation was provided. Experiment was run on E-Prime 2.0. Auditory primes were presented binaurally at a constant sound level via headphones. Visual stimuli were presented in white letters over a black background in the computer screen. Each trial started with a fixation cross in the center of the screen. After 100 msec, the onset of the auditory prime took place. The fixation cross remained until 100 msec after the offset of the auditory prime. Then, the visual target appeared immediately after on the center of the screen during 2000 msec. Participants had to decide (as fast and accurately as they could) whether the stream of letters formed a real word or a nonword, by pressing either "f" or "j" in the keyboard. After that, the program presented a black screen for 2000 msec. Eight practice trials were presented before the experimental block, in which participants received feedback about their accuracy and response times. Trials were randomly presented to participants, who were explicitly asked to try to avoid blinking their eyes throughout the presentation of each trial.

2.5. *EEG recordings, preprocessing and analyses*

The EEG signal was recorded from 60 active electrodes mounted in an elastic cap at standard 10–20 locations. Eye movements were monitored with three additional electrodes located around the right eye, providing vertical and horizontal EOG. Also, the on-line reference electrode was attached to the left mastoid, and another electrode was attached to the right mastoid. Inter-electrode impedance was kept below 10 kΩ. Data was acquired at a sampling rate of 500 Hz while filtered on-line between .1 and 100 Hz. EEG marks were time-locked to presentation of the visual targets.

EEG recordings were preprocessed following Makoto's preprocessing pipeline (2021). More concretely, first we used EEGLAB (Delorme & Makeig, 2004) to downsample the data to 250 Hz. Next, we high-pass filtered the data at 1 Hz. Then, we removed bad channels using the function *clean_rawdata*, and interpolated all the removed channels. After that, we re-referenced the data to average, removed line noise using the function *cleanline*, and run ICA analyses to reject eye-blink components in the recordings. Finally, we epoched the data from −100 to 1200 msec relative to the presentation of the visual target, applying baseline correction on the epochs from −100 msec to target onset.

As previous studies on lexical-semantic processing during foreign-accented speech comprehension have shown that using different analysis parameters (e.g., different electrode regions) can lead to different results (Strauber et al., 2021), we used two different strategies to analyze the EEG recordings. First, we used EEGLAB's STUDY statistics to run a 2-way ANOVA on the N400 component (300–500 msec after targets' onset; Kutas & Federmeier, 2011) scalp topographies, applying permutation statistics with FDR correction for multiple comparisons, which results in scalp topographies for the different experimental conditions and the associated *p*-value maps for main effects and interactions. Secondly, and following Luck and Gaspelin (2017) guidelines for avoiding spurious results in EEG experiments, we established an a priori time window (300–500 msec) and electrode sites (averaging over 23 centro-parietal electrodes: C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P7, P5, P3, P1, Pz, P2, P4, P5, P8) to analyze the modulations of the N400 component (based on Kutas & Federmeier, 2011).

To complement this latter approach (and the repeated measures (RM) ANOVAs used to analyze response times in the behavioral task), we conducted Bayesian analyses of effects across matched models in JASP. The Bayes inclusion factor (BF_{incl}, which indicates the evidence in favor of the alternative hypothesis) was calculated for those effects that were significant when following the frequentist approach. Alternatively, the Bayes exclusion factor (BF_{excl}, indexing the evidence in favor of the null hypothesis) was obtained for those effects that were not significant when following the frequentist approach.

3. Results

3.1. *Behavioral results*

Since accuracy responses are binomial (hit, miss), the accuracy data were submitted to a logit mixed models analysis. There was a significant main effect of *relatedness* (*Estimate* = −1.62, *SE* = .55, *z* = −2.91, *p* = .004). Post-hoc comparisons showed that participants were more accurate when responding to repeated and related (*M* for both conditions = 99.65%) than unrelated targets (*M* = 97.85%; *Estimate* = −.60, *SE* = .12, *z* = −4.87, $p < .001$). Neither the main effect of *accent* (*Estimate* = −.10, *SE* = .31, *z* = −.34, *p* = .73), nor the interaction between the two factors (*Estimate* = −.29, *SE* = .31, *z* = −.97, *p* = .33), was significant.

As for reaction times, we conducted a RM ANOVA. Again, we found a significant main effect of *relatedness*, $F(1.60,36.87) = 80.38$, $MSE = 3230.85$, $p < .001$, $\eta_p^2 = .78$ (BF_{incl} = 2.03E + 25, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests showed that participants reacted more rapidly to repeated than related ($p < .001$, $d = 1.41$) and unrelated ($p < .001$, $d = 2.58$) targets, and more rapidly to related than unrelated targets ($p < .001$, $d = 1.17$). Additionally, we observed a significant interaction between *accent* and *relatedness*, $F(1.56,35.96) = 3.77$, $MSE = 1268.74$, $p = .042$, $\eta_p^2 = .14$ ($BF_{incl} = .60$, unrealiable data). However, Holm corrected post-hoc tests showed that there were no differences in any of the *relatedness* levels when compared according to the *accent* in which primes were

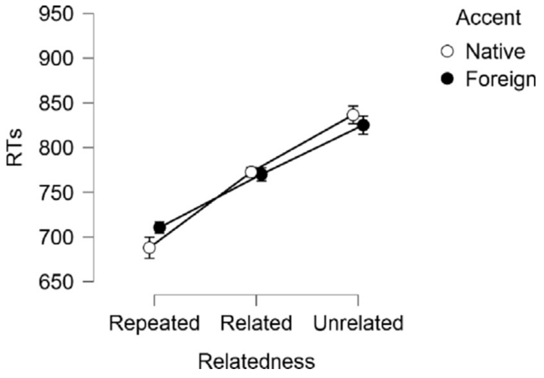

Fig. 1 – Mean response times (RTs) to visual targets.

presented (all p values > .11; Fig. 1). Finally, the main effect of *accent* was not significant, $F(1,23) = .14$, $MSE = 2156.69$, $p = .71$, $\eta_p^2 = .006$ ($BF_{excl} = 5.28$, data more likely under the null *vs* alternative hypothesis).

3.2. EEG results

The ERPs averaged on electrode CP4 (where the effects were more noticeable) can be seen in Fig. 2.

The analysis carried out in EEGLAB's STUDY statistics showed a significant main effect of *relatedness* distributed over centro-parietal and frontal/lateral electrodes (p values < .001; Fig. 3). The main effect of *accent* was marginally non-significant (p values $\geq$ .05) over some midline and lateral electrodes, with slightly more negative N400 amplitudes for targets preceded by primes uttered by foreign-accented than native speakers. Finally, the interaction between the two factors was not significant on any region of the scalp (p values = 1).

To further explore the main effect of *relatedness*, 1-way ANOVAs on the N400 scalp distributions of each possible comparison were performed. Repeated targets elicited less negative N400 amplitudes than related and unrelated targets (p values < .001; Fig. 4) over centro-parietal electrodes, and more negative N400 amplitudes at frontal/lateral electrodes. However, the difference between related and unrelated targets was only marginally non-significant (p values > .05) over central and left-posterior electrodes.

On the other hand, the RM ANOVA on the N400 amplitudes averaged over the a priori selected centro-parietal electrodes showed a significant main effect of *relatedness*, $F(1.37,30.04) = 16.96$, $MSE = .47$, $p < .001$, $\eta_p^2 = .43$ ($BF_{incl} = 1.24E + 7$, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests showed that the N400 amplitudes were less negative for repeated than related ($p < .001$, $d = .88$) and unrelated ($p < .001$, $d = 1.16$) targets, but that there were no significant differences between related than unrelated targets ($p = .19$, $d = .28$). The main effect of *accent* ($F(1,22) = 2.64$, $MSE = .20$, $p = .118$, $\eta_p^2 = .11$; $BF_{excl} = 2.08$, data more likely under the null *vs* alternative hypothesis) and the interaction between the two factors ($F(2,44) = 1.09$, $MSE = .20$, $p = .344$, $\eta_p^2 = .05$; $BF_{excl} = 4.44$, data more likely under the null *vs* alternative hypothesis) were not significant (Fig. 5).

4. Discussion

In this study, we aimed to explore whether foreign-accented speech could hinder the sound-to-meaning mapping. Behavioral and EEG results suggest that this is not the case: participants processed cross-modally repeated words more easily than targets semantically related (or unrelated) to the primes, and they processed targets semantically related to the primes more easily than unrelated targets. This was the case regardless of whether primes were produced by a native Spanish speaker or by a French foreign-accented speaker of Spanish.

These results are consistent with those earlier studies showing that there are no overall differences between the lexical-semantic processing (as indexed by the N400) that takes place while listeners hear sentences produced by native or foreign-accented speakers (Hanulíková et al., 2012; Holt et al., 2018; Foucart et al., 2020). In addition, the results are congruent with the scientific literature on adaptation to foreign-accented speech, which has repeatedly shown that listeners adapt easily and quickly to this auditory signal, supporting the flexibility of lexical recognition processes (e.g., Bradlow & Bent, 2008; Clarke, 2000; Clarke & Garrett, 2004). Thus, although we used a different experimental paradigm (i.e., cross-modal priming) and type of stimuli (i.e., visual instead of auditory) than those used in these previous studies, we managed to achieve comparable results. Moreover, we obtained analogous results to those of previous experiments

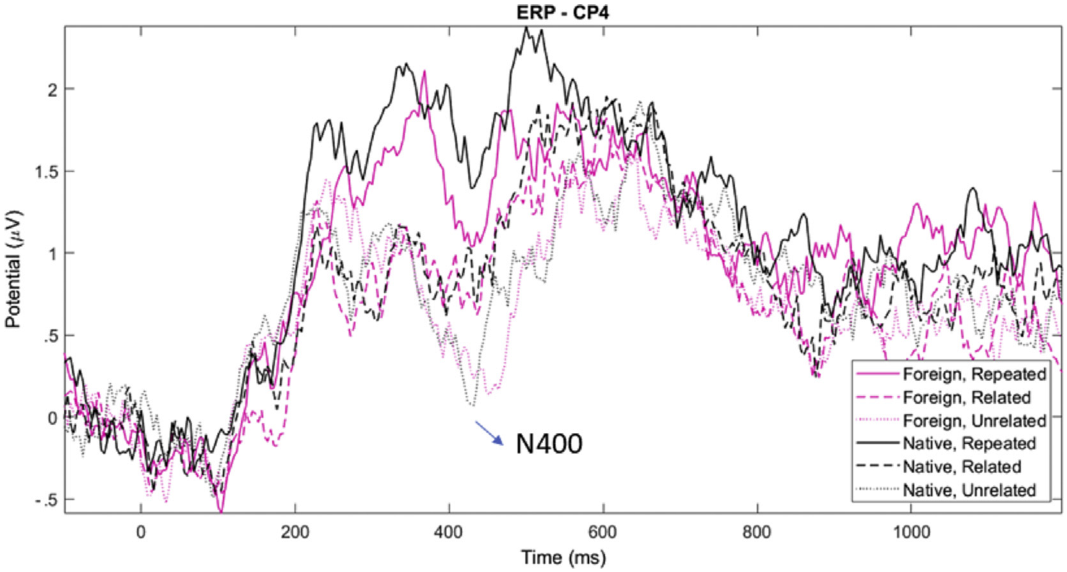

Fig. 2 – ERPs averaged on electrode CP4. The waveforms of all 23 electrodes that were included in the analysis of the a priori selected centro-parietal region are presented in the Supplementary materials.

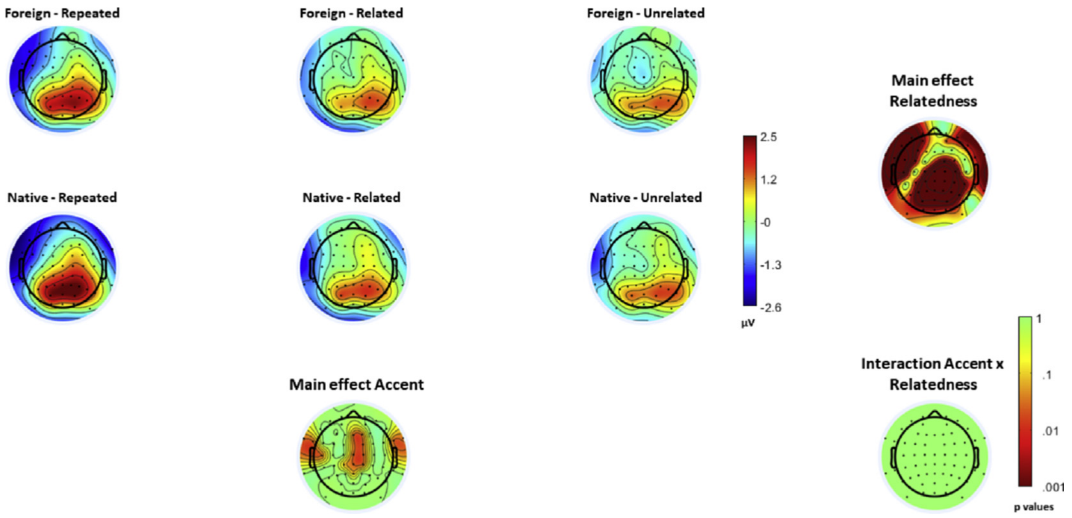

Fig. 3 – **Scalp topographies and associated *p*-value maps for the main effects of relatedness (top-right map), accent (bottom-left map), and the interaction between the two factors (bottom-right map).**

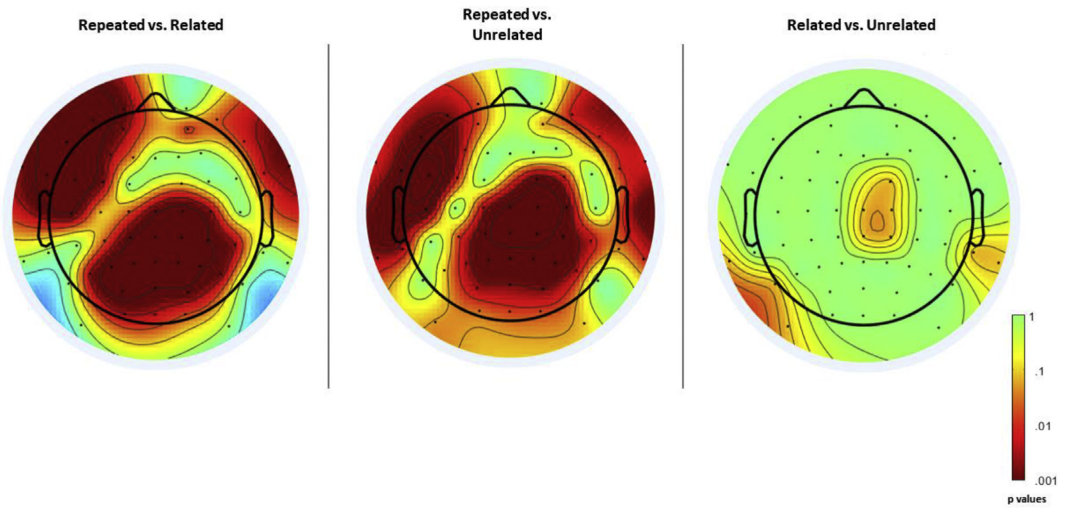

Fig. 4 – ***p*-value maps for the comparisons between the three levels of the relatedness factor.**

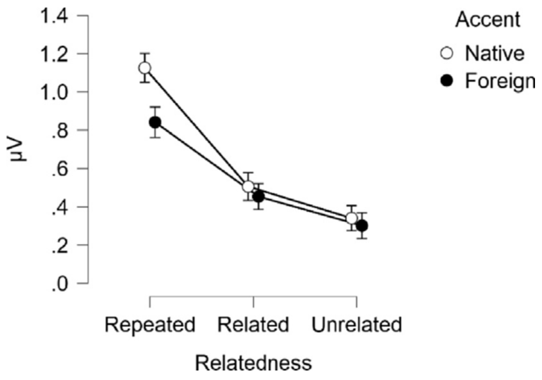

Fig. 5 – **Mean N400 amplitudes to visual targets averaged over centro-parietal electrodes.**

with very similar tasks that used white noise (*vs* a clear speech signal) instead of foreign-accented (*vs* native) speech: almost identical semantic priming effects for directly related pairs (e.g., boat–ship) irrespective of whether the acoustic signal was more or less difficult to process (e.g., Angwin et al., 2018). Therefore, our results suggest that foreign-accented speech does not hinder the sound-to-meaning mapping.

Importantly, our findings seem to support the more recent perspectives on speech processing arguing that the sound-to-meaning mapping would not be hindered by the acoustic variability and perceptual invariance caused by speech signals that are unusual for us (e.g., Hickok & Poeppel, 2007; Rauschecker & Scott, 2009). Although listening to someone and understanding what they are telling us seems like an effortless task, in our daily lives we are confronted with different speakers who have very different ways of producing speech sounds, depending on biological, geographic, or incidental factors (Stevens & Blumstein, 1981). Perhaps it is precisely for this reason that our brains can deal with this variability in the acoustic signal, working simultaneously on accessing lexical and phonological representations while the properties of the acoustic signal remain available to the processing system (e.g., Gwilliams, Poeppel, et al., 2018; Gwilliams, Linzen, et al., 2018b). More concretely, acoustic representations would remain preserved in the auditory cortex while, in parallel, commitments to phonological categories or lexical representations are established and can be revised later (Gwilliams, Linzen, et al., 2018). This may explain our results, as listeners could activate the lexical-semantic representations of foreign-accented words in a similar way as when listening to native speech, even though the acoustic representations were still active in case it was necessary to revise the former.

However, our results contradict those of previous literature showing differences in lexical-semantic processing when listeners hear native versus foreign-accented speech. It should be noted that these previous studies obtained very dissimilar observations: larger N400 effects when processing foreign-accented versus native speech (Romero-Rivas et al., 2015, 2016); the opposite pattern (Xu et al., 2020); or delayed/time-dilated N400 effects when listening to foreign-accented versus native speech (Grey & van Hell, 2017; Grey et al., 2020; Gosselin et al., 2021). As pointed out above, these discrepancies could be explained, at least partially, by the variability of analysis parameters (Strauber et al., 2021); and/or by the acoustic differences (e.g., word duration) between the stimuli presented in the native and foreign-accented conditions used in these earlier studies, which in turn could have affected the point of auditory uniqueness between conditions and altered the latency and amplitude of the N400 in uncontrolled ways (O'Rourke & Holcomb, 2002). In contrast, we obtained similar results when using different analysis parameters (i.e., analyses focused on the entire scalp *vs* region of interest), and we matched the stimuli in the native and foreign-accented conditions by using visual targets. That highlights the robustness of our methodology, and stresses the relevance of using visual stimuli, or more controlled auditory stimuli (e.g., by setting the ERP triggers at the points of auditory uniqueness, rather than at word onset; O'Rourke & Holcomb, 2002), for future research in this field of study.

In addition to the main results, we would like to discuss two other minor results. First, we observed differences in semantic priming between behavioral and EEG findings (i.e., we obtained significant differences between related and unrelated targets only in the behavioral measures, not in the N400 analyses). This is congruent with previous studies showing that semantic priming effects are observed for response times but not for the N400 when masking (Brown & Hagoort, 1993) or degrading the prime (Holcomb, 1993), suggesting that spreading activation (i.e., a fast acting mechanism that does not require attention or awareness, through which semantically related nodes are almost automatically activated when encoding a word; Posner & Snyder, 1975; Shiffrin & Schneider, 1977) influences RTs, but not the N400. Although in our study we did not mask the primes, nor did they appear degraded, as they were produced half of the time by a foreign-accented speaker, a situation similar to that of these previous studies could have occurred (but see section 5). Secondly, we observed a frontal/lateral negativity in response to repeated versus related/unrelated targets in the N400 time window (300–500 msec after target presentation). This effect, with reversed polarity in comparison to the centro-parietally distributed N400, could be explained by the average reference method used in the processing of the EEG recordings, which usually leads to positive effects along with negative effects (Li et al., 2018; Luck, 2014). Therefore, future studies using the average reference approach should be cautious in interpreting reverse polarity effects in the N400 time window.

Finally, we must acknowledge some potential limitations of the study. On the one hand, the stimuli of the foreign-accented condition were recorded by a single speaker, who had a specific accent (a French accent when speaking Spanish), and therefore it would be daring to try to generalize our results to any situation involving a foreign-accented speaker. Although we cannot be sure of this because we did not measure it in our study, it could be that, for instance, our participants were more familiar with the French accent than with other foreign accents, and that could have affected the results (Holt et al., 2018). Similarly, the French foreign-accented speaker of Spanish received a moderate score on the accent rating (2.87, with 5 being the maximum, and 1 being native speech). Even though the accent of the foreign speaker was perceived as significantly more foreign than that of the native speaker in our study, it is well established that mild foreign accents are less difficult to understand than strong foreign accents, and that listeners require more time to process words produced with a strong versus mild foreign accent (Witteman et al., 2013, 2015; Porretta et al., 2016). Hence, it could be that we did not find an effect of speakers' accent on the sound-to-meaning mapping because the foreign-accented speaker in our study had a mild accent.

To further explore these potential limitations, we conducted a second experiment. We used the same experimental paradigm and materials, except that, in this case, the stimuli for the foreign-accented condition were produced by a speaker with a different (German), stronger accent.

5. Study 2

5.1. *Method*

5.1.1. *Participants*

We recruited 22 participants from the Center for Brain and Cognition database (12 women, mean age = 23.52; range = 18–34 years). As in the previous study, all were native Spanish speakers, right-handed, had normal or corrected to normal visual and hearing acuity, and took part in the experiment in return for monetary compensation (10€/h).

The study was approved by the Academic Board of the Universitat Pompeu Fabra, the experiment was conducted according to the principles expressed in the Declaration of Helsinki, and we obtained written informed consent from all participants.

5.1.2. *Materials*

Materials were the same used in the previous study, but this time the foreign-accented primes were uttered by a German foreign-accented speaker of Spanish. Accent strength and intelligibility were rated by the same participants as before (these participants did not take part in the main studies, and measurements were obtained between studies 1 and 2).

Regarding accent strength, the German foreign-accented speaker was rated with a strong accent (4.23 out of 5), and her accent was perceived as stronger than the French accent used in the previous study ($t(1,21) = 9.69$; $p < .001$). As for intelligibility, participants recognized 94% of the words uttered by the German speaker (the words that were not recognized varied between participants). Although this was a very good performance, intelligibility of the German-accented speaker was poorer compared to the other two speakers (*vs* French speaker, $t(1,8) = 3.83$; $p < .01$; *vs* native speaker, $t(1,8) = 8.98$; $p < .001$).

The design, procedure, and EEG recordings, preprocessing and analyses were similar to the ones used in the previous study.

5.2. Results

5.2.1. *Behavioral results*

We carried out a logit mixed models analysis to explore accuracy. We obtained a significant main effect of *relatedness* (*Estimate* $= -.78$, *SE* $= .30$, $z = -2.60$, $p = .009$). Post-hoc comparisons showed that participants were similarly accurate when responding to repeated ($M = 99.24\%$) and related targets ($M = 98.79\%$; *Estimate* $= -.27$, *SE* $= .31$, $z = -.88$, $p = .38$). Also, that they were less accurate when responding to unrelated ($M = 96.74\%$) than repeated (*Estimate* $= -.74$, *SE* $= .19$, $z = -3.82$, $p < .001$) or related targets (*Estimate* $= -.49$, *SE* $= .21$, $z = -2.31$, $p = .021$). The main effect of *accent* (*Estimate* $= -.05$, *SE* $= .19$, $z = -.27$, $p = .79$) and the interaction between the two factors (*Estimate* $= -.06$, *SE* $= .21$, $z = -.27$, $p = .79$) were not significant.

The RM ANOVA for reaction times showed a significant main effect of *relatedness*, $F(2,42) = 98.89$, $MSE = 1326.27$, $p < .001$, $\eta_p^2 = .82$ ($BF_{\mathrm{incl}} = 1.88E + 15$, data substantially more likely under the alternative *vs* null hypothesis; Fig. 6). Holm corrected post-hoc tests showed that participants reacted more rapidly to repeated than related ($p < .001$, $d = 1.74$) and unrelated ($p < .001$, $d = 2.98$) targets, and more rapidly to related than unrelated targets ($p < .001$, $d = 1.25$). The main effect of *accent* was marginally non-significant, $F(1,21) = 4.12$, $MSE = 813.12$, $p = .06$, $\eta_p^2 = .16$ ($BF_{\mathrm{excl}} = 1.08$, data slightly more likely under the null *vs* alternative hypothesis), with participants responding slightly slower after foreign-accented primes ($M = 711.79$, $SE = 23.71$) compared to native primes ($M = 701.72$, $SE = 23.71$). Finally, the interaction between the two factors was also not significant, $F(2,42) = 1.93$, $MSE = 576.39$, $p = .16$, $\eta_p^2 = .08$ ($BF_{\mathrm{excl}} = 3.41$, data more likely under the null *vs* alternative hypothesis).

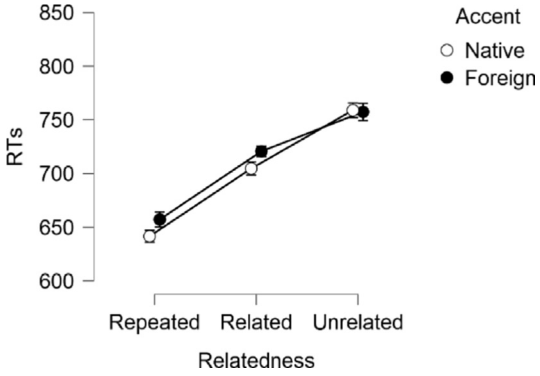

Fig. 6 – Mean response times (RTs) to visual targets in Study 2.

5.2.2. *EEG results*

The ERPs averaged on electrode CP4 (where the effects were more noticeable) can be seen in Fig. 7.

EEGLAB's STUDY statistics showed a significant main effect of *relatedness* distributed over centro-parietal, frontal and frontal/lateral electrodes (p values $< .001$; Fig. 8). The main effect of *accent* and the interaction between the two factors were not significant (p values $= 1$).

As in the previous study, we carried out 1-way ANOVAs on the N400 scalp distributions of each possible comparison to further explore the main effect of *relatedness*. Repeated targets elicited less negative N400 amplitudes than related and unrelated targets (p values $< .001$; Fig. 9) over centro-parietal electrodes, and more negative N400 amplitudes at frontal/lateral electrodes. However, the difference between related and unrelated targets was not significant (p values $> .01$).

The repeated measures ANOVA on the N400 amplitudes averaged over the centro-parietal electrodes showed a significant main effect of *relatedness*, $F(1.47,30.82) = 33.82$, $MSE = .66$, $p < .001$, $\eta_p^2 = .62$ ($BF_{\mathrm{incl}} = 1.13E + 12$, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests showed that the N400 amplitudes were less negative for repeated than related ($p < .001$, $d = 1.28$) and unrelated ($p < .001$, $d = 1.68$) targets, but that the differences between related and unrelated targets was marginally non-significant ($p = .07$, $d = .39$). The main effect of *accent* ($F(1,21) = .20$, $MSE = .33$, $p = .65$, $\eta_p^2 = .01$; $BF_{\mathrm{excl}} = 5.02$, data more likely under the null *vs* alternative hypothesis) and the interaction between the two factors ($F(2,42) = .79$, $MSE = .34$, $p = .46$, $\eta_p^2 = .04$; $BF_{\mathrm{excl}} = 4.88$, data more likely under the null *vs* alternative hypothesis) were not significant (Fig. 10).

5.2.3. *Cross-studies analyses*

In order to properly compare the results of the two studies, we carried out complementary analyses taking into account the data from both studies, and adding the between-subjects factor *study* (1 *vs* 2).

Regarding behavioral results, the logit mixed models analysis of accuracy yielded a significant main effect of *study* (*Estimate* $= -.44$, *SE* $= .15$, $z = -2.92$, $p = .003$): participants in study 1 ($M = 99.05\%$) were slightly more accurate than participants in study 2 ($M = 98.26\%$). We also obtained a main effect of *relatedness* (*Estimate* $= -.98$, *SE* $= .21$, $z = -4.64$, $p < .001$). Post-hoc comparisons showed that participants were less accurate when responding to unrelated ($M = 97.32$) versus repeated ($M = 99.46\%$; *Estimate* $= -.89$, *SE* $= .26$, $z = -3.42$, $p < .001$) or related targets ($M = 99.24\%$; *Estimate* $= -.74$, *SE* $= .20$, $z = -3.61$, $p < .001$); however, they did not show significant differences when responding to repeated and related targets (*Estimate* $= -.31$, *SE* $= .62$, $z = -.49$, $p = .62$). All other main effects and interactions were not significant ($ps > .34$).

The RM ANOVA for reaction times showed a significant main effect of *relatedness*, $F(1.67,76.71) = 167.57$, $MSE = 910.44$,

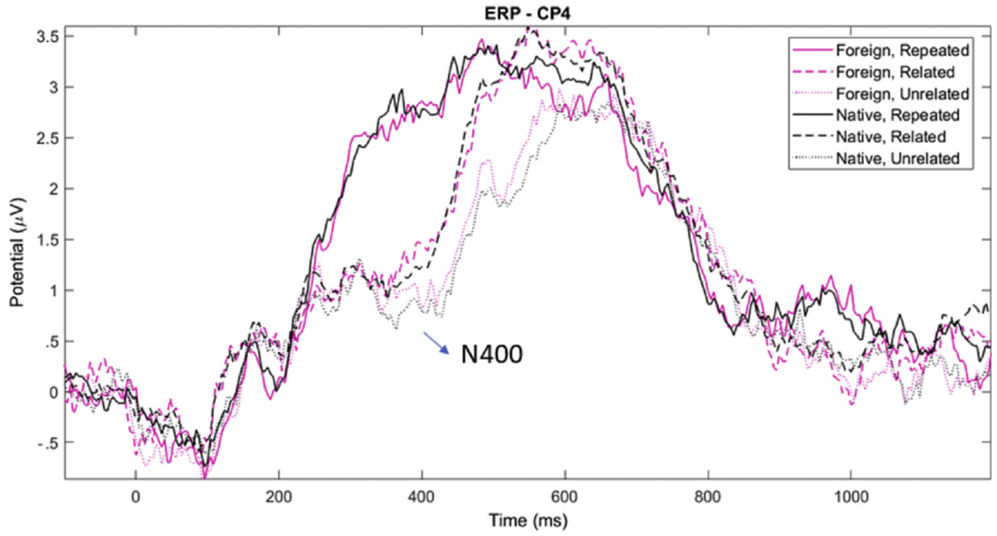

Fig. 7 – ERPs averaged on electrode CP4, Study 2. The waveforms of all 23 electrodes that were included in the analysis of the a priori selected centro-parietal region are presented in the Supplementary materials.

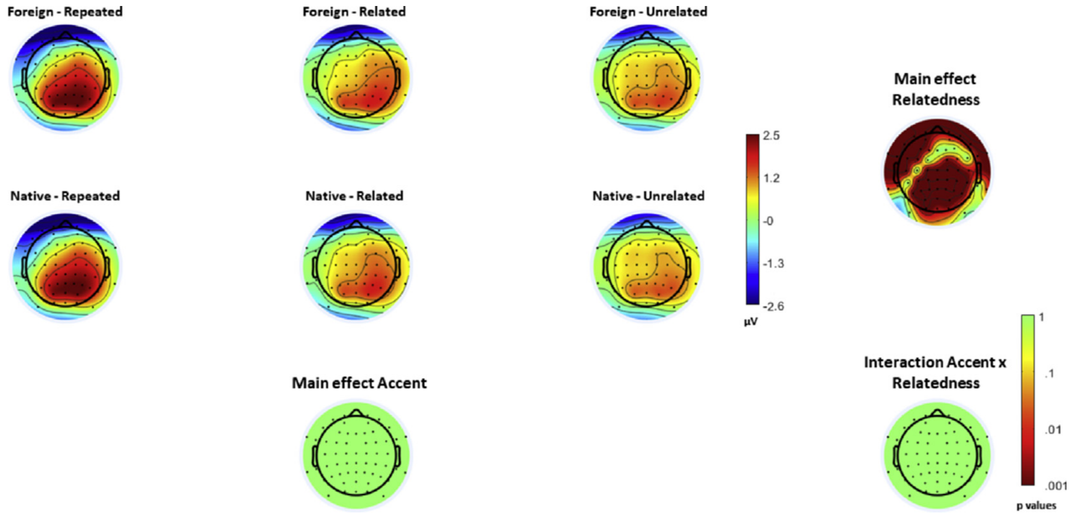

Fig. 8 – Study 2 – Scalp topographies and associated *p*-value maps for the main effects of relatedness (top-right map), accent (bottom-left map), and the interaction between the two factors (bottom-right map).

$p < .001$, $\eta_p^2 = .79$ ($\mathrm{BF_{incl}} = 7.32\mathrm{E} + 52$, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests showed that unrelated targets were processed more slowly than related ($p < .001$, $d = 1.18$) and repeated targets ($p < .001$, $d = 2.69$), and that related targets were processed more slowly than repeated targets ($p < .001$, $d = 1.52$). All other main effects and interactions were not significant ($Fs < 1.92$, $ps > .17$, $\mathrm{BF_{excl}} > 2.10$).

As for the EEG results, we only carried out the repeated measures ANOVA on the N400 amplitudes averaged over the a priori selected centro-parietal electrodes, since EEGLAB's STUDY statistics do not allow for global analyses with more than two factors. This analysis showed a main effect of *relatedness*, $F(1.43,84.80) = 51.07$, $MSE = .11$, $p < .001$, $\eta_p^2 = .54$ ($\mathrm{BF_{incl}} = 2.91\mathrm{E} + 26$, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests showed that the N400 amplitudes were more negative for unrelated versus related ($p = .02$, $d = .34$) or repeated targets ($p < .001$, $d = 1.44$), and for related compared to repeated targets ($p < .001$, $d = 1.10$). We also obtained a main effect of *study*, $F(1,43) = 5.32$, $MSE = 3.98$, $p = .03$, $\eta_p^2 = .11$ ($\mathrm{BF_{incl}} = 2.46$, data slightly more likely under the alternative *vs* null hypothesis), and a significant interaction between *relatedness* and *study*, $F(1.43,84.80) = 3.93$, $MSE = .11$, $p = .04$, $\eta_p^2 = .08$ ($\mathrm{BF_{incl}} = 27.11$, data substantially more likely under the alternative *vs* null hypothesis). Holm corrected post-hoc tests for the interaction showed that the N400 amplitude for repeated targets was more negative in study 1 versus 2 ($p = .02$), but that the amplitudes for related and unrelated targets did not differ significantly between studies ($ps = .50$ and $.94$, respectively). All other effects and interactions involving the factor *accent* were not significant ($Fs < 3.33$, $ps > .08$, $\mathrm{BF_{excl}} > 2.64$).

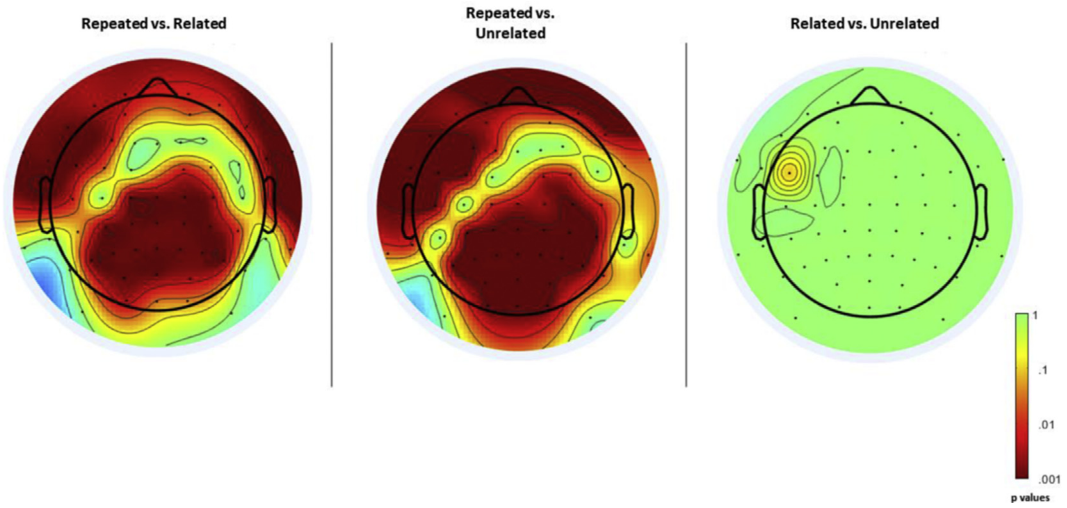

Fig. 9 – Study 2 – *p*-value maps for the comparisons between the three levels of the relatedness factor.

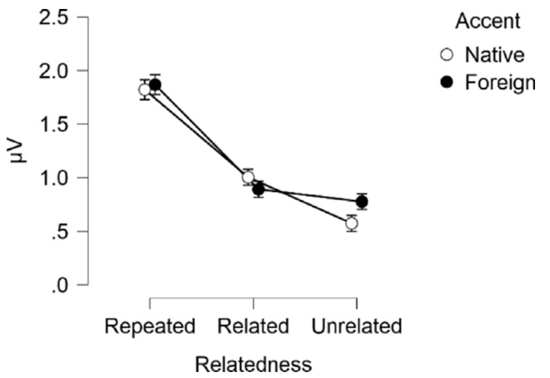

Fig. 10 – Mean N400 amplitudes to visual targets averaged over centro-parietal electrodes in Study 2.

6. Discussion

In this second study, we explored whether a different and stronger foreign accent than the one used in the first study could modulate the sound-to-meaning mapping. Nevertheless, we replicated the results of study 1: regardless of whether primes were produced by the native or the foreign-accented speaker, participants processed repeated targets more easily than related or unrelated targets, and related more easily than unrelated targets. Although this latter pattern was only significant in the behavioral analyses (but not in the N400 analyses, as in study 1), it also became significant for the neural data when the results of both studies were considered together. This is possibly due to the increased statistical power in the cross-studies analyses, as the number of participants taken into account doubled.

The only difference we observed between the two studies (beyond a small difference in participants' percentage of hits on the behavioral task) was that the amplitude of the N400 for repeated targets was more negative in study 1 versus 2, irrespective of the accent in which the primes were uttered. This could simply be due to individual differences in neural activity between the subjects who participated in the two studies. Alternatively, participants in study 2 could have adopted a processing strategy more dependent on lexical information than participants in study 1 when dealing with the auditory primes, which in turn would reduce lexical activation when presented with the same words cross-modally repeated (see Goslin et al., 2012). However, it is important to note that this pattern was not observed for related or unrelated targets, nor did it interact with the accent in which the auditory primes were produced, suggesting that sound-to-meaning mapping processes were not modulated by accent or across studies.

We believe these results are doubly important. On the one hand, we show that although listeners usually need more time to adapt to foreign-accented speech when speakers have a strong accent (e.g., Witteman et al., 2013, 2015), accent strength does not seem to affect the online sound-to-meaning mapping. Again, this result supports theoretical perspectives suggesting that acoustic variability in the speech signal need not affect the sound-to-meaning mapping (e.g., Hickok & Poeppel, 2007; Rauschecker & Scott, 2009), as well as those empirical studies showing that we can commit to phonological categories or lexical representations even though acoustic representations are still active in case the former needs to be revised (Gwilliams, Poeppel, et al., 2018; Gwilliams, Linzen, et al., 2018b). On the other hand, by obtaining an almost perfect replication of the results of the first study, we could be bringing more stability to a field of study where results have been very contradictory up to now (Strauber et al., 2021). Thus, we again stress the importance of using materials in which the native and foreign-accented conditions are as equal as possible, either using visual materials or, alternatively, auditory materials in which the point of auditory uniqueness is controlled (see O'Rourke & Holcomb, 2002).

7. General discussion

Across two studies, we found moderate evidence that speakers' accent does not affect the sound-to-meaning mapping. More specifically, in a cross-modal priming paradigm, we showed that listeners were able to access lexical-semantic representations of (visually presented) targets with the same ease/difficulty regardless of whether the primes were uttered by native or foreign-accented speakers. Our results suggest that this process is flexible and, as discussed above, support theoretical perspectives and empirical evidence arguing that the brain simultaneously processes information from the acoustic signal while accessing lexical or phonological representations (Hickok & Poeppel, 2007; Rauschecker & Scott, 2009; Gwilliams, Poeppel, et al., 2018; Gwilliams, Linzen, et al., 2018b). That is, ambiguity in the speech signal can be neutralized to some extent, without the need to discard it, while the brain simultaneously transforms the acoustic input into discrete categories and keeps the acoustic properties of the speech signal available in case the former need to be reanalyzed (e.g., Gwilliams, Linzen, et al., 2018). Similar results have been found in the visual modality: the brain can maintain low-level representations (e.g., the orientation or brightness of the lines forming a digit or a letter) while generating high-level representations of the input signal (Gwilliams & King, 2020). Taken together, the evidence would suggest that this computational strategy could be generalizable to various domains, modalities, or tasks.

Although we strongly believe this to be the case, we cannot entirely discount other theoretical perspectives that suggest that the sound-to-meaning mapping is a more sequential process, but that it can be subsequently corrected by top-down mechanisms. For instance, ambiguous speech sounds could be disambiguated thanks to complementary lexical information that feeds back activation to the phoneme representation (e.g., Ganong, 1980). In fact, some studies focusing on the lexical-semantic processing of foreign-accented speech have suggested that this might be precisely the mechanism that may be at work during sentence comprehension: as prelexical normalization would not be possible when listening to foreign-accented speech, that would increase listeners' reliance on lexical cues (Goslin et al., 2012). Critically, however, this increased reliance on lexical information should generate a pattern of reduced lexical-semantic activation (i.e., reduced N400 amplitude) during foreign-accented versus native speech comprehension (Goslin et al., 2012), and we did not observe such a pattern. Therefore, once again, we believe that this alternative explanation does not fit our data very well, but we acknowledge that future studies in this field should further explore this issue. For example, by manipulating the phonological neighborhood density of the stimuli, we could test whether items with higher values in this parameter generate a pattern of greater reduction in lexical-semantic activation when listening to foreign-accented versus native speech, which would support theoretical perspectives such as the TRACE model (McClelland & Elman, 1986).

Of course, our results would not necessarily generalize to any type of task/process in which the comparison between native and foreign-accented speech is involved. For instance, there could be double dissociations between speech perception tasks/processes (more dependent on the dorsal stream, responsible for transforming the speech signal into articulable phonological representations), and speech recognition/comprehension tasks/processes (more dependent on the ventral stream, responsible for mapping the speech signal onto conceptual and semantic representations; Hickok & Poeppel, 2007). In fact, this seems to be the case. The Phonological Mapping Negativity (an ERP that appears approximately 200–400 msec after the onset of auditory stimuli, and that indexes the mapping of acoustic information onto phonological representations; Connolly & Phillips, 1994) is sensitive to the continuum of foreign accentedness, presenting more negative amplitudes the more foreign-accented speakers productions move away from the native-like speech signal (Porretta et al., 2017). Likewise, tasks in which participants have to focus more on processing the similarity/difference between an acoustic prime and a visual target would result in behavioral differences when being presented with stronger versus milder foreign accents (Porretta et al., 2016; Witteman et al., 2013, 2015). That suggests that foreign-accented speech does indeed modulate speech perception processes. Additionally, future studies could explore whether the sound-to-meaning mapping mechanisms are modulated during the first moments of exposure to foreign-accented speech, when listeners have not yet been able to adapt to the variability of the acoustic signal (e.g., during the first minute of exposure; Clarke & Garrett, 2004).

We must acknowledge and discuss some potential limitations in our studies. First, since we used a cross-modal semantic priming paradigm in which auditory primes were produced by native or foreign-accented speakers, but targets were presented visually, it could be the case that the lexical-semantic processing of foreign-accented words was already solved by the time the visual targets were presented. However, we doubt that this is the case: the interstimulus interval (time elapsed from the offset of the prime to onset of the target) was set at 100 msec, and studies on foreign-accented (and native) speech comprehension show that lexical-semantic processing continues well beyond auditory words' offset (e.g., Grey & van Hell, 2017; Romero-Rivas et al., 2015). Secondly, most previous EEG studies on lexical-semantic processing during foreign-accented speech comprehension have focused on the N400 effect elicited by words related/unrelated to the sentences in which they were embedded. Although the predictive/integration processes involved in sentence comprehension and semantic priming paradigms may be somewhat similar, the predictability of natural language is likely to be less extreme (Lau et al., 2016; Smith & Levy, 2013). Hence, future studies in this field should continue to explore lexical-semantic processing of foreign-accented speech in the context of sentence comprehension, but using more controlled materials (e.g., visual targets embedded in auditory sentences, or auditory targets time-locked at the point of auditory uniqueness). Finally, when analyzing the effects/interactions involving the factor *accent* following the Bayesian approach, we obtained mostly moderate (i.e., $BF_{excl} > 3$ and <10), and sometimes weak ($BF_{excl} > 1$ and <3), evidence supporting the null hypothesis (i.e., no effect/interaction involving the factor *accent*). Thus, although we obtained similar results in the two studies (using both frequentist and Bayesian statistics), suggesting that speakers' accents do not affect the sound-to-meaning mapping, this latter observation leaves a small window open to the possibility of finding an effect of speakers' accent on lexical-semantic processing in future studies employing a methodology similar to ours (but, importantly, we should not confuse moderate/weak support for the null hypothesis with moderate/strong support for the alternative hypothesis, as $BF_{excl} > 2$ translates into $BF_{incl} < .50$; e.g., van Doorn et al., 2021).

Before concluding, we believe it is necessary to re-emphasize the importance of the results of these studies. For the first time, we were able to replicate (almost perfectly) the observations of an electrophysiological study on the processing of foreign-accented speech. As we have repeatedly pointed out throughout the manuscript, this field of study has so far yielded very contradictory findings (e.g., Strauber et al., 2021). Although we believe that it is still important to explore the role that listeners' familiarity with the accents they process (Grey & van Hell, 2017), or listeners' own idiosyncratic characteristics (Holt et al., 2018), may play in understanding foreign-accented speech (and the role of these factors in experimental designs that rely on sentences *vs* single words as stimuli), our results suggest that the speaker's accent does not, in general, affect the sound-to-meaning mapping. In addition, we show the same pattern of results not only across two different studies, but also across different types of measurements (behavioral and EEG), analyses (frequentist and Bayesian), and EEG data analysis parameters (permutation statistics for scalp topographies, and analyses of the region of interest). This indicates the importance of using materials that are as evenly matched as possible between the native and foreign-accented speech conditions, as well as using different analysis parameters within the same study, at least until this field of research begins to offer more reliable patterns of results.

Open practices

The study in this article earned an Open Data and Open Materials badges for transparent practices. Data and Materials for this study can be found at: https://osf.io/ry953/?view_only=24ff649856894421a31a6e3fb63d1eef.

Author contributions

Carlos Romero-Rivas: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing. Albert Costa: Conceptualization, Funding acquisition, Methodology, Supervision.

Declaration of competing interest

None.

Acknowledgments

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No part of the study procedures or analyses was pre-registered prior to the research being conducted. In the manuscript, we reported how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the studies.

Study materials, data and analyses codes are available in the following link: https://osf.io/7c4ve/.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2022.01.009.

REFERENCES

Angwin, A. J., Wilson, W. J., Copland, D. A., Barry, R. J., Myatt, G., & Arnott, W. L. (2018). The impact of auditory white noise on semantic priming. *Brain and Language, 180*–*182*, 1–7. https://doi.org/10.1016/j.bandl.2018.04.001

Bradlow, A. R., & Bent, T. (2008). Perceptual adaptation to non-native speech. *Cognition, 106*(2), 707–729. https://doi.org/10.1016/j.cognition.2007.04.005

Brown, C., & Hagoort, P. (1993). The processing nature of the N400: Evidence from masked priming. *Journal of Cognitive Neuroscience, 5*(1), 34–44. https://doi.org/10.1162/jocn.1993.5.1.34

Clarke, C. M. (2000). Perceptual adjustment to foreign-accented English. *Journal of the Acoustical Society of America, 107*(5), 2856. https://doi.org/10.1121/1.429245

Clarke, C. M., & Garrett, M. F. (2004). Rapid adaptation to foreign-accented English. *The Journal of the Acoustical Society of America, 116*(6), 3647–3658. https://doi.org/10.1121/1.1815131

Connolly, J. F., & Phillips, N. A. (1994). Event-related potential components reflect phonological and semantic processing of the terminal word of spoken sentences. *Journal of Cognitive Neuroscience, 6*(3), 256–266. https://doi.org/10.1162/jocn.1994.6.3.256

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Eurostat. (2021). Migration and migrant population statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Migration_and_migrant_population_statistics#:~:text=%3A%20Eurostat%20(migr_imm2ctz)-,Migrant%20population%3A%2023%20million%20non%2DEU%20citizens%20living%20in%20the,5.1%20%25%20of%20the%20EU%20population.

Fernández, A., Díez, E., & Alonso, M. A. (2003). Normas de asociación libre en castellano. https://iblues-inico.usal.es/iblues/nalc_home.php.

Foucart, A., Costa, A., Morís-Fernández, L., & Hartsuiker, R. J. (2020). Foreignness or processing fluency? On understanding the negative bias toward foreign-accented speakers. *Language Learning, 70*(4), 974–1016. https://doi.org/10.1111/lang.12413

Ganong, W. F. (1980). Phonetic categorization in auditory word perception. *Journal of Experimental Psychology: Human Perception* *and Performance, 6*(1), 110–125. https://psycnet.apa.org/doi/10.1037/0096-1523.6.1.110.

Goslin, J., Duffy, H., & Floccia, C. (2012). An ERP investigation of regional and foreign accent processing. *Brain and Language, 122*(2), 92–102. https://doi.org/10.1016/j.bandl.2012.04.017

Gosselin, L., Martin, C. D., Navarra-Barindelli, E., & Caffarra, S. (2021). The presence of a foreign accent introduces lexical integration difficulties during late semantic processing. *Language, Cognition and Neuroscience*, 1–21. https://doi.org/10.1080/23273798.2021.1909084

Grey, S., Cosgrove, A. L., & van Hell, J. G. (2020). Faces with foreign accents: An event-related potential study of accented sentence comprehension. *Neuropsychologia, 147*, 107575. https://doi.org/10.1016/j.neuropsychologia.2020.107575

Grey, S., & van Hell, J. G. (2017). Foreign-accented speaker identity affects neural correlates of language comprehension. *Journal of Neurolinguistics, 42*, 93–108. https://doi.org/10.1016/j.jneuroling.2016.12.001

Gwilliams, L., & King, J. R. (2020). Recurrent processes support a cascade of hierarchical decisions. *eLife, 9*, Article e56603. https://doi.org/10.7554/eLife.56603

Gwilliams, L., Linzen, T., Poeppel, D., & Marantz, A. (2018). In spoken word recognition, the future predicts the past. *Journal of Neuroscience, 38*(35), 7585–7599. https://doi.org/10.1523/JNEUROSCI.0065-18.2018

Gwilliams, L., Poeppel, D., Marantz, A., & Linzen, T. (2018). Phonological (un)certainty weights lexical activation. In *Proceedings of the 8th workshop on cognitive modelling and computational linguistics (CMCL 2018)* (pp. 29–34). https://doi.org/10.18653/v1/W18-0104

Hanulíková, A., Van Alphen, P. M., Van Goch, M. M., & Weber, A. (2012). When one person's mistake is another's standard usage: The effect of foreign accent on syntactic processing. *Journal of Cognitive Neuroscience, 24*(4), 878–887. https://doi.org/10.1162/jocn_a_00103

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*(5), 393–402. https://doi.org/10.1038/nrn2113

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology, 30*(1), 47–61. https://doi.org/10.1111/j.1469-8986.1993.tb03204.x

Holcomb, P. J., & Anderson, J. E. (1993). Cross-modal semantic priming: A time-course analysis using event-related brain potentials. *Language and cognitive processes, 8*(4), 379–411. https://doi.org/10.1080/01690969308407583

Holt, R., Kung, C., & Demuth, K. (2018). Listener characteristics modulate the semantic processing of native vs. foreign-accented speech. *PLoS One, 13*(12), Article e0207452. https://doi.org/10.1371/journal.pone.0207452

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology, 62*, 621–647. https://doi.org/10.1146/annurev.psych.093008.131123

Lau, E. F., Gramfort, A., Hämäläinen, M. S., & Kuperberg, G. R. (2013). Automatic semantic facilitation in anterior temporal cortex revealed through multimodal neuroimaging. *Journal of Neuroscience, 33*(43), 17174–17181. https://doi.org/10.1523/JNEUROSCI.1018-13.2013

Lau, E. F., Weber, K., Gramfort, A., Hämäläinen, M. S., & Kuperberg, G. R. (2016). Spatiotemporal signatures of lexical–semantic prediction. *Cerebral Cortex, 26*(4), 1377–1387. https://doi.org/10.1093/cercor/bhu219

Li, Y., Wang, Y., Zhang, B., Wang, Y., & Zhou, X. (2018). Electrophysiological responses to expectancy violations in semantic and gambling tasks: A comparison of different EEG reference approaches. *Frontiers in Neuroscience, 12*, 169. https://doi.org/10.3389/fnins.2018.00169

Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19*(1), 1–36. https://doi.org/10.1097/00003446-199802000-00001

Luck, S. J. (2014). *An introduction to the event-related potential technique*. MIT Press.

Luck, S. J., & Gaspelin, N. (2017). How to get statistically significant effects in any ERP experiment (and why you shouldn't). *Psychophysiology, 54*(1), 146–157. https://doi.org/10.1111/psyp.12639

MacGregor, L. J., Pulvermüller, F., Van Casteren, M., & Shtyrov, Y. (2012). Ultra-rapid access to words in the brain. *Nature Communications, 3*, 711. https://doi.org/10.1038/ncomms1715

Makoto's preprocessing pipeline. (n.d.). Retrieved March 9, 2021 from https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline.

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition, 25*(1–2), 71–102. https://doi.org/10.1016/0010-0277(87)90005-9

McBride, K. (2015). Which features of Spanish learners' pronunciation most impact listener evaluations? *Hispania, 98*(1), 14–30. https://www.jstor.org/stable/24368849.

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology, 18*(1), 1–86. https://doi.org/10.1016/0010-0285(86)90015-0

O'Rourke, T. B., & Holcomb, P. J. (2002). Electrophysiological evidence for the efficiency of spoken word processing. *Biological Psychology, 60*(2–3), 121–150. https://doi.org/10.1016/S0301-0511(02)00045-5

Porretta, V., Tremblay, A., & Bolger, P. (2017). Got experience? PMN amplitudes to foreign-accented speech modulated by listener experience. *Journal of Neurolinguistics, 44*, 54–67. https://doi.org/10.1016/j.jneuroling.2017.03.002

Porretta, V., Tucker, B. V., & Järvikivi, J. (2016). The influence of gradient foreign accentedness and listener experience on word recognition. *Journal of Phonetics, 58*, 1–21. https://doi.org/10.1016/j.wocn.2016.05.006

Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 55–85). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Rauschecker, J. P., & Scott, S. K. (2009). Maps and streams in the auditory cortex: Nonhuman primates illuminate human speech processing. *Nature neuroscience, 12*(6), 718–724. https://doi.org/10.1038/nn.2331

Romero-Rivas, C., Martin, C. D., & Costa, A. (2015). Processing changes when listening to foreign-accented speech. *Frontiers in Human Neuroscience, 9*, 167. https://doi.org/10.3389/fnhum.2015.00167

Romero-Rivas, C., Martin, C. D., & Costa, A. (2016). Foreign-accented speech modulates linguistic anticipatory processes. *Neuropsychologia, 85*, 245–255. https://doi.org/10.1016/j.neuropsychologia.2016.03.022

Romero-Rivas, C., Thorley, C., Skelton, K., & Costa, A. (2019). Foreign accents reduce false recognition rates in the DRM paradigm. *Journal of Cognitive Psychology, 31*(5–6), 507–521. https://doi.org/10.1080/20445911.2019.1634576

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84*(2), 127–190. https://psycnet.apa.org/doi/10.1037/0033-295X.84.2.127.

Smith, N. J., & Levy, R. (2013). The effect of word predictability on reading time is logarithmic. *Cognition, 128*(3), 302–319. https://doi.org/10.1016/j.cognition.2013.02.013

Stevens, K. N., & Blumstein, S. E. (1981). The search for invariant acoustic correlates of phonetic features. *Perspectives on the study of speech*, 1–38.

Strauber, C. B., Ali, L. R., Fujioka, T., Thille, C., & McCandliss, B. D. (2021). Replicability of neural responses to speech accent is driven by study design and analytical parameters. *Scientific reports, 11*, 4777. https://doi.org/10.1038/s41598-021-82782-4

van Doorn, J., van den Bergh, D., Böhm, U., Dablander, F., Derks, K., Draws, T., Etz, A., Evans, N. J., Gronau, Q. F., Haaf, J. M., Hinne, M., Kucharský, š., Ly, A., Marsman, M., Matzke, D., Komarlu Narendra Gupta, A. R., Sarafoglou, A., Angelika Stefan, Voelkel, J. G., & Wagenmakers, E. J. (2021). The JASP guidelines for conducting and reporting a Bayesian analysis. *Psychonomic Bulletin & Review, 28*(3), 813–826.

Witteman, M. J., Bardhan, N. P., Weber, A., & McQueen, J. M. (2015). Automaticity and stability of adaptation to a foreign-accented speaker. *Language and Speech, 58*(2), 168–189. https://doi.org/10.1177/0023830914528102

Witteman, M. J., Weber, A., & McQueen, J. M. (2013). Foreign accent strength and listener familiarity with an accent codetermine speed of perceptual adaptation. *Attention, Perception, & Psychophysics, 75*(3), 537–556. https://doi.org/10.3758/s13414-012-0404-y

Xu, J., Abdel Rahman, R., & Sommer, W. (2020). Perceived language competence modulates criteria for speech error processing: Evidence from event-related potentials. *Language, Cognition and Neuroscience, 35*(6), 752–765. https://doi.org/10.1080/23273798.2018.1562558