Electrophysiological Signatures of English Onomatopoeia

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Electrophysiological Signatures of English Onomatopoeia

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Abstract

Onomatopoeia are widespread across the world's languages. They represent a relatively simple iconic mapping: the phonological/phonetic properties of the word evokes acoustic related features of referents. Here, we explore the EEG correlates of processing onomatopoeia in English. Participants were presented with a written cue-word (e.g., leash) and then with a spoken target-word. The target word was either an onomatopoeia (e.g., bark), a sound-related but arbitrary word (e.g., melody) or another arbitrary word (e.g., bike). Participants judged whether the cue and the target word were similar in meaning. We analysed Event-Related Potentials (ERPs) in different time-windows: (i) early (100-200 and 200-250ms) to assess differences in processing at the form-level; (ii) the N400 time window (300-500ms) in order to establish if there are differences in semantic processing across our word-types; (iii) late (600-900ms) to assess post-lexical effects. We found that onomatopoeia differed from the other words in the N400 time-window: when cue and target were unrelated, onomatopoeic words led to greater negativity which can be accounted for in terms of enhanced semantic activation of onomatopoeia which leads to greater salience of the mismatch. We discuss results in the context of a growing body of literature investigating iconicity in language processing and development.

Keywords: Iconicity, Onomatopoeia, EEG, ERP, N400, Word processing

Introduction

In a paper entitled 'The Origin of Speech' (1960), Charles Hockett claimed that "in a semantic communicative system, the ties between meaningful message-elements and their meanings can be arbitrary or nonarbitrary. In language the ties are arbitrary. The word 'salt' is not salty nor granular; dog is not 'canine'; 'whale' is a small word for a large object; 'microorganism' is the reverse" (Hockett 1960: 6). However, as acknowledged by Hockett himself, if arbitrariness provides limitless possibilities to linguistic communication in terms of what can be communicated about, it also "has the disadvantage of being arbitrary" (Hockett 1960: 6). The lacking of an intrinsic connection between the phonological level and the semantic or conceptual level poses impediments especially to lexical acquisition and processing: how can we effortlessly learn and use words when no hint to what they stand for is provided by their shape? And, why isn't iconicity more widespread across languages? These and related questions are presently at the core of a growing number of studies that investigate iconicity and arbitrariness in language development and language processing (e.g., Lockwood and Dingemanse, 2015; Lupyan and Winter, 2018; Perniss et al., 2010).

Non-arbitrary mappings are generally defined as 'iconic'-- an 'icon' being "a sign which stands for something merely because it resembles it" (Peirce, 1931-36: §3.362) -- linguistic 'iconicity' being a sensory-perceived resemblance between properties of linguistic form and properties of meaning (Taub, 2001). Although traditionally dismissed as a marginal phenomenon in structural accounts of language (Chomsky, 1988; De Saussure, 1916; Hockett, 1960), iconicity plays a central role in recently-developed research programs grounded on embodied theories of human cognition (Meteyard et al., 2012; Vigliocco et al., 2014). Such programs adopt a functional view of communication where arbitrariness and iconicity co-exist to facilitate learning and processing. Arbitrariness is assumed to allow for the efficient transmission of an unbounded array of concepts; iconicity is deemed instrumental in mapping language onto human experience as the content of linguistic communication. In particular, iconic mechanisms have been proposed to link lexical items to the cognitive representation/re-enactment of the sensorimotor experience associated with real-world referents, thus facilitating the acquisition and processing of lexical meaning (Perniss and Vigliocco, 2014).

Iconicity and Onomatopoeia in Languages

Iconicity is more than a marginal exception in linguistic systems (Dautriche et al., 2017; Dingemanse, 2012; Voeltz and Kilian-Hatz, 2001), although the degree of iconicity varies across modalities (spoken and signed) and languages. Spoken languages show limited iconicity, possibly due to the reduced amount of experience that can be iconically represented in oral-aural modality. However, this is not to say that spoken languages (especially Indo-European languages) are *iconically challenged,* as iconicity is readily visible in the gestures speakers produce in interactional contexts and in their use of prosody (see Vigliocco et al., 2014 for a discussion).

In speech, a prominent form of iconicity is represented by onomatopoeia, *i.e.*, lexical representations of acoustic events (e.g. ‘bubble’, ‘crash’, ‘tweet’ in English). Onomatopoeic words preserve in their form acoustic properties of the environmental sounds they copy. These iconic words tend to follow the phonotactic/phonological conventions of the language they belong to, hence, while a rooster in English-speaking countries would go ‘cock-a-doodle-doo’, a rooster in Italy would say ‘chicchirichì’. In addition to onomatopoeia, the amount of iconic material in lexica varies greatly (Berlin and O’Neill, 1981; Dingemanse, 2012; Jakobson and Waugh, 2002), with a number of languages outside the Indo-European family presenting recognizable sets of 'ideophone' or 'mimetic' words (see Perniss et al., 2010 for a description). Indo-European languages like English do not have such a recognizable set of iconic words besides onomatopoeia, they do have however other forms of iconicity embedded in the lexicon, such as indirect iconicity (Sidhu & Pexman, 2017): e.g., the link between specific phonemes (e.,g., /i/) and semantic features (e.g., small). These types of indirect iconicity can be near universal: Blasi et al (2016) compared the forms of 100 basic terms across 4,298 languages and found, in addition to other patterns, that words for the concept small tended to include the high-front vowel /i/.

There is evidence that onomatopoeia and more generally iconic words may be easier to learn (e.g. Kantartzis et al., 2011; Laing, 2014, 2019; Lockwood et al., 2016; Nygaard et al., 2009). Evidence further suggests that onomatopoeia are among the first words being produced by babies. Laing (2014) showed that onomatopoeia made up the majority of early vocabulary for a German baby (< 12mo). Perry et al (2018) showed that iconic words are used more often by 10-26 months old infants, and then, their production decreases. Onomatopoeia are also common in caregivers' language early on and then decrease (Vigliocco et al., 2019). In sign language (British Sign Language, BSL) it has been found that more iconic signs are learnt before less iconic ones (Thompson et al., 2012).

With regard to word processing, there is far less behavioural evidence supporting any advantage for onomatopoeic and generally iconic words. Meteyard and colleagues (2015) showed that onomatopoeia were better recognized as words by aphasic patients than tightly matched arbitrary words. While Peeters (2016) failed to observe any difference in lexical decisions for onomatopoeic and arbitrary words in Dutch, Sidhu et al. (in press), found a significant advantage for onomatopoeia in a visual lexical decision task as well as in a task that explicitly engaged phonology. In sign languages, there are now studies spanning four different languages (BSL, ASL, NGT and DGL) showing effects of iconicity on sign recognition using different paradigms (e.g. Grote and Linz, 2003; Ormel et al., 2009; Thompson et al., 2009, 2012; Vinson et al., 2015). Thus, we have limited results for onomatopoeia in different populations, tasks and languages suggesting that any of these factors may affect whether facilitation is present.

Electrophysiological Evidence for a Different Status of Onomatopoeia

Less than a handful of studies have considered the Event-Related Potentials (ERPs) elicited by iconic words (including onomatopoeia) so far, providing mixed results. Two studies reported difference between iconic and non-iconic words in early time windows (Lockwood and Tuomainen, 2015; Peeters, 2016). In Lockwood and Tuomainen (2015) Japanese speakers were asked to read sentences in which a plausible or implausible target word was either iconic (a mimetic/ideophone) or an arbitrary word. They found that the P2 component (252-256ms) was more positive for the iconic words. As P2 is normally associated with phonological processing and multisensory integration, they inferred that the larger P2 was triggered by the combination of 1) phonological processing of salient features of Japanese iconic words (e.g. reduplication), and 2) multisensory integration between word form and sensory information associated with the mimetic words. In an auditory lexical decision task with Dutch speakers, Peeters (2016) found that an early component (N2, 150-200ms) showed decreased negativity for onomatopoeia vs. arbitrary words, suggesting early processing differences between onomatopoeia and other words. A final study by Egashira et al. (2015), where iconic words were auditorily presented to Japanese speakers, did not find any difference for early components.

Results are equally mixed when considering the N400 component. Peeters (2016) found that onomatopoeic words elicited less negative N400 (350-550ms) compared with arbitrary words, suggesting that iconicity may facilitate access to semantic information. Less negative

ERP around 400ms for iconic words was also found by Lockwood and Tuomainen (2015) and Egashira (2015). However, because of differences in temporal and spatial distribution, the authors did not consider this component as N400. Finally, all three experiments reported a difference for the Late Positive Complex (LPC), normally associated with post-lexical processing and meta-linguistic decisions between onomatopoeic and arbitrary words. Nevertheless, while Lockwood and Tuomainen (2015) observed more positive LPC for iconic words between 400-800ms and Peeters (2016) between 600-800ms, Egashira et al. (2015) reported more negative early LPC (200-500ms) and middle LPC (500-900ms) for onomatopoeia vs. arbitrary words.

To sum up, the few available studies that have assessed neurophysiological differences between processing iconic and less iconic words have provided mixed results, which may have multiple causes. First, conflicting patterns may come about as a consequence of cross-linguistic differences, as for example, Japanese mimetic words tend to have repeated moras, whereas this is not necessarily the case for Dutch onomatopoeia. Second, the results may be due to semantic differences between onomatopoeia and other iconic words used. Onomatopoeia refer to sound, however, iconicity is not limited to the acoustic dimension. We do not know whether this might matter. Finally, different studies used different tasks that engage semantic processing to different extents.

The Present Study

Here, we focus on onomatopoeia in English. We use a clearly semantic task and we provide a comparison between onomatopoeia and other, more arbitrary, words also related to sound. We employed a semantic association task where we asked participants to judge the relatedness between visually presented words (cues) and spoken target words (onomatopoeia and arbitrary). The semantic task was selected because we wanted to ensure that both phonological features and semantic information was processed, so that we can observe the full electrophysiological signature of onomatopoeia. In contrast to previous experiments where lexical and sub-lexical differences between onomatopoeia and control words were not carefully controlled, we compared onomatopoeia with two groups of arbitrary words: arbitrary words from different semantic classes – matched on a large number of psycholinguistics dimensions, but crucially also a group of arbitrary words that, just like onomatopoeia, are rich in sensory features and that refer to sound (e.g., words like ‘music’). We included this third group to ensure that any difference in electrophysiological responses to the onomatopoeia cannot be accounted for in terms of semantic differences between these words and control words, given that in embodied accounts all words referring to sound should activate sensory features relating to sound (see e.g., Kiefer et al., 2008). Moreover, in contrast to previous studies, we carefully matched onomatopoeic and arbitrary words for valence, as studies have found iconic words (especially mimetics in Japanese) to have more emotional associations than arbitrary words (Iwasaki, Vinson & Vigliocco, 2007) and emotional valence has been shown to affect N2 and N400 amplitude (e.g. Kanske and Kotz, 2007).

If onomatopoeia involve direct mappings between phonological/phonetic features and semantic features (Vigliocco and Kita, 2006); or if they involve additional links from semantic to (multi)sensory areas (Kanero et al., 2014), we should observe differences in the N400 component of the Event-Related Potentials (ERP) elicited by onomatopoeic vs. other words. Moreover, if any difference in the phonology of onomatopoeia and arbitrary words also have processing consequences, we should see differences in earlier time windows, reflecting the sensory processing of the words. If onomatopoeia and arbitrary words differ in post-lexical processing, we should see difference in LPC (600-900ms).

Method

Stimulus materials

Fifty target words were selected in each category (onomatopoeic, sound-related arbitrary; other arbitrary words). Stimuli were taken from materials used in previous studies investigating iconicity effects (Meteyard and Vigliocco, 2015) and for which information about their semantic properties were available (Vinson and Vigliocco, 2008, Brysbaert et al., 2014, Lynott, 2009, 2013, McRae, 2005; see Supplementary Materials, table 16 for a full list of the stimuli). Across the three groups, words were matched for concreteness (Brysbaert et al. 2014), number of syllables, number of phonemes, number of letters, and log transformed frequency, orthographic neighbourhood density and phonological neighbourhood density generated from English Lexicon Project's HAL corpus (Balota et al. 2007). One-way ANOVA confirmed that the three categories did not differ in any of these lexical features. For each word, we chose a related and an unrelated word to use as a cue (e.g. 'leash'/ 'sad' for the target onomatopoeia 'bark'; 'chord'/'envy' for the target sound related word 'melody'; 'ride'/ 'history' for the target other arbitrary word 'bike').

An on-line norming study with 20 monolingual native British speakers was performed to ensure the difficulty of the task was matched across word categories. Each participant was presented with either a related or unrelated cue and then the target word, and was asked to judge the relatedness by pressing yes/no buttons on the screen as fast and as accurately as possible. ANOVAs showed that RTs and accuracy did not differ significantly across word-type conditions. However, unrelated pairs were significantly more accurate ($F(1,19)=12.971$, $p=0.002$, $\eta_p^2. = 0.406$) and required longer response time ($F(1,19)=5.632$, $p=0.028$, $\eta_p^2= 0.229$) than related pairs. Based on these results, we also replaced one target word, 5 cues and removed one target word, leaving 147 target words in total. It is important to note here that we did not control for whether the association between cue and target was related to sound or not. In our final list of items, most of the onomatopoeic words were not related in sound to the cue words (42/49); however, for the sound-related arbitrary words, 21/49 were related in sound. We avoided using onomatopoeia as cue words, however, some of the cue words are iconic, according to available iconicity norms[1]. A female native speaker of British English produced the target words at a normal rate, recorded in a soundproof booth. The stereophonic stimuli had sampling frequency of 44,100 Hz, and intensity scale's absolute peak normalized to 0.3 dB with Praat (v. 6.0.19., Boersma, 2001) and duration between 450-900ms.

Participants

Thirty-one native English speakers (mean age=25) were recruited through the UCL Psychology Subject Pool. All participants were right-handed (assessed using Edinburgh Handedness Inventory), with normal or corrected to normal vision, normal hearing and without neurological disorders. Data from seven participants were excluded due to technical problems and/or accuracy below 80%. Twenty-four participants were included in the analysis (Female=11).

Procedure

Participants were seated 100cm in front of a computer in a shielded booth. The experiment was programmed with Presentation® software (Version 18.0, www.neurobs.com), with auditory stimuli presented through EEG-compatible headphones. Written instructions explained to participants that they would first see a written word on the screen, then hear a word immediately afterwards, and their task was to judge whether the written word and the following spoken word were related in meaning. Participants were presented with 12 practice trials before the experiment. Hand of response was counterbalanced across participants.

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[1] It was not possible to include iconicity of the cue as a control variable in the analyses because too many of our cue words do not have iconicity ratings in existing databases.

Two lists of stimuli were counterbalanced across participants, each containing 147 target words and 49 fillers and correspondent cues (50% related and unrelated), so that no participant heard a target word twice. The stimuli were divided into six blocks, randomized within lists and across participants.

In each trial, a fixation cross was presented for 700ms, and was then followed by the written cue presented for 700ms. 1000ms after the end of the cue, the audio target stimuli was presented. No response deadline was set. The next trial began after a 1000ms inter-trial interval. Participants took breaks between blocks. The experimental procedure was approved by the UCL Division of Psychology and Language Science ethics committee.

EEG recording

A BioSemi Active Two system was used for EEG recording. 32 silver-silver chloride (Ag-AgCl) electrodes were applied following a 10-10 international system layout. Common reference included CMS electrode serving as online reference and DRL electrode serving as ground electrode. There were four external electrodes in addition of the scalp sites: one below left eye (VEOG) and one on the right canthus (HEOG) to measure vertical and horizontal eye movement; two on the mastoids as reference in offline processing. To check for relative impedance differences, the electrode offsets were kept between +/-25mV.

The continuous EEG was referenced offline to the average of two mastoids and downsampled to 256 Hz. Due to the stimulus-onset asynchrony (SOA) in the target stimuli, the EEG waveform was time-locked to the actual onset of the word in the audio recording, not the onset of recording. To do that, we annotated the SOA in each stimulus with Praat (v. 6.0.29., Boersma, 2001), and edited the eventlists of each participant by adding SOA to the onset of the auditory stimuli using EEGLAB (v.14.1.1, Delorme and Makeig, 2004) and ERPLAB (v.7.0.0, Lopez-Calderon and Luck, 2014). EEG waveform was epoched from -200 to 900ms, corrected using -200 to 0ms as baseline and filtered with 0.1-100Hz band-pass filter. Independent component analysis (ICA) (Chaumon et al., 2015) and artefact rejection was further performed to remove noise from the data (Mean=11.088%, SD=13.733 across participants. Rejection rate was similar across two relatedness levels and three word types). Based on previous literature (Lockwood & Dingemanse, 2015; Peeters, 2016; Lockwood and Tuomainen, 2015; Egashira et al., 2015), we focused on N1 (100-200ms), P2 (200-250ms), N400 (300-500ms) and LPC (600-900ms) responses. The averaged ERP was calculated for those time intervals from 9 electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) (Luck, Vogel & Shapiro, 1996). All of the components above are largest at midline (Fz, Cz, Pz). Adding the left and right side electrodes next to the electrodes above, provides a fair estimate of the scalp distribution on the anterior/posterior and laterality planes across the different conditions in our study. However for completeness, we further carried out analyses including all electrodes (see supplementary materials).

Data Analysis

Linear mixed effect regression (LMER) analyses were performed for both behavioural and EEG data by participant and by item using LME4 package (Bates et al., 2015) in R version 3.4.1(R studio team, 2016). For both behavioural and EEG data, two analyses were performed. In the first, we considered iconicity as a categorical variable and we contrasted three word types (onomatopoeic, sound-related arbitrary and other arbitrary words). In the second, we considered iconicity as a continuous variable using ratings of iconicity collected by Lu et al. (in prep). These ratings were obtained online in a survey in which 49 English speakers were asked to judge the iconicity of 320 words on a 1 (not iconic) to 7 (highly iconic) scale. Ratings were available for 47/49 onomatopoeic words and 33/49 sound related words. Thus, this secondary analysis excluded the other arbitrary words.

Behavioural Analysis

We used LMER to analyse response time (RT) data (ms) and Logistic LMER for accuracy (0/1). The independent variables included word type (onomatopoeia, control, sound related), relatedness (related, unrelated), and relatedness*word type. Further, log frequency (van Heuven et al., 2014), age of acquisition (Kuperman et al, 2012), concreteness (Brysbaert et al., 2014) and duration of stimulus were included as control variables. To capture by item and by participant variance, we included participant and word as random intercept. All continuous variables were standardized. Significance of the critical interaction between relatedness and word type was established by comparing models with and without the interaction term using ANOVA, which is a built-in function of R performing Wald Chi-squared tests for LMER. Significant interactions were further analysed by comparing least square means using emmeans package in R (Lenth, 2018).

The second analysis was conducted with the same process, with the exception that this analysis only contrasted onomatopoeic and sound-related arbitrary words (for which we had ratings of iconicity) and included iconicity as a continuous variable, rather than as a categorical variable. Here, significance of the interaction iconicity*relatedness was directly computed by the model without the need to carry out model comparison. We further included in the random structure iconicity, relatedness and iconicity*relatedness as random slope.

ERP Analysis

In the first and second LMER analysis of ERP (μV), we added three control variables to the ones listed above for the behavioural analysis: RT of the trial, mean accuracy of the item and electrode site. The electrode sites were coded as 2 variables, one for left/right (left=-1, centre=0, right=1), and one for frontal/parietal (frontal=-1, centre=0, parietal=1) (Emmorey et al., 2017). All continuous variables were standardized. Significance of interactions was established as above. Only correct trials were analysed.

Results

Behavioural Results

RTs

Table 1. RT's Descriptive Statistics (ms).

Condition	*n*	*M*	*SD*
*Related onomatop*oeia (e.g. leash-bark)	523	1119	481
Unrelated onomatopoeia (e.g. sad-bark)	518	1137	448
Related sound-related (e.g. chord-melody)	527	1166	459
Unrelated sound-related (e.g. envy-melody)	519	1225	451
Related other arbitrary (e.g. ride-bike)	514	1156	616
Unrelated other arbitrary (e.g. history-bike)	528	1231	541

The main LMER analysis found a significant main effect of relatedness ($ß_{unrelated}$ =0.07, p=<.001): judgement for related pairs were faster than for unrelated trials. There was also a significant main effect of duration (ß= 0.17, p<.001): longer auditory stimuli, not surprisingly, led to longer RTs. No other effects were significant. See Table 1 for descriptive statistics.

Similarly, the second analysis found significant positive mean effect of duration (ß= 0.14, p<.001) on mean RT. But the relatedness effect was not significant. No other significant effect was found. See Table 1-2 in Supplementary Materials for full results.

Accuracy

Table 2. Accuracy's Descriptive Statistics

Condition	*n*	*M*	*SD*
Related onomatopoeia (e.g. leash-bark)	523	0.860	0.347
Unrelated onomatopoeia (e.g. sad-bark)	518	0.952	0.215
Related sound-related (e.g. chord-melody)	527	0.911	0.285
Unrelated sound-related (e.g. envy-melody)	519	0.969	0.173
Related other arbitrary (e.g. ride-bike)	514	0.887	0.317
Unrelated other arbitrary (e.g. history-bike)	528	0.979	0.143

In the first binary logistic regression, we found a significant main effect of relatedness ($ß_{unrelated}$=0.72, p<.001): participants were less accurate for related than unrelated pairs. No other significant effect was found. See Table 2 for descriptive statistics. The same negative effect of relatedness ($ß_{unrelated}$=0.77, p<.001) was also found in second analysis, showing a consistent effect. No other main effect or interaction were significant. See Tables 3-4, Supplementary Materials, for full results.

EEG Results

Figure 1 depicts the ERP responses for the nine electrodes analysed in the main analysis with condition as the predictor variable. Figure 2 shows the ERP response in the second analysis with iconicity as predictor.

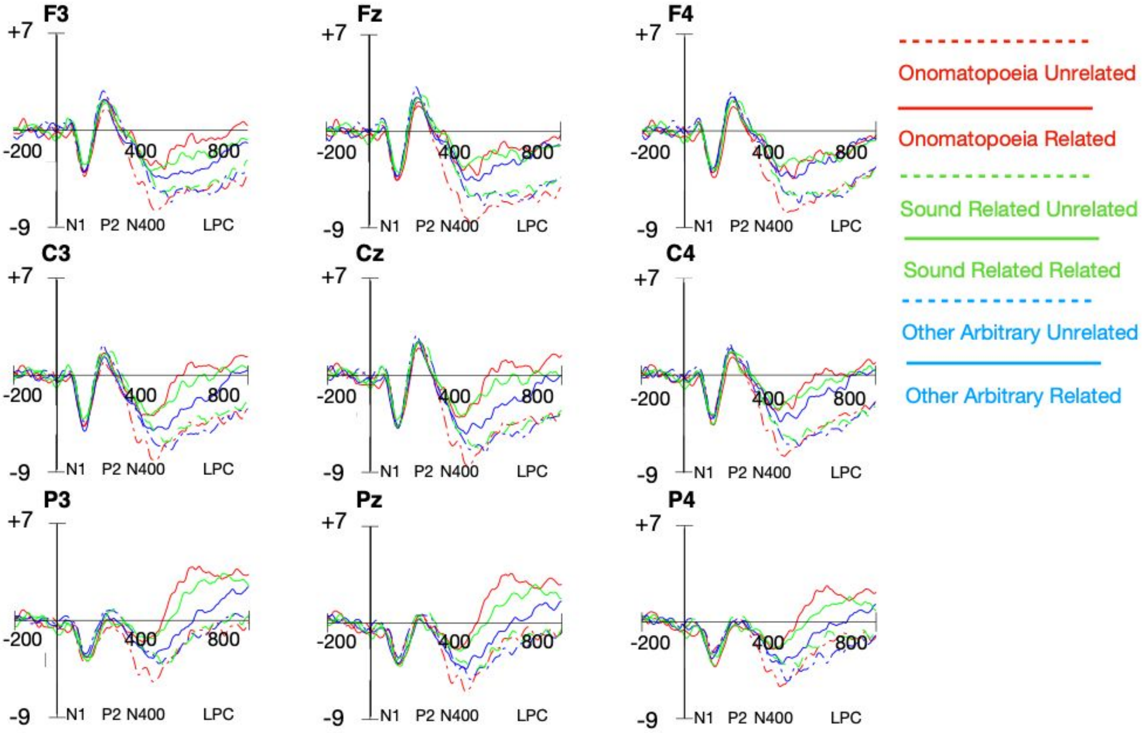

Figure 1. ERP plot of word type * relatedness in N1, P2, N400, and LPC. The plot was additionally filtered with 30Hz low pass filter for illustration.

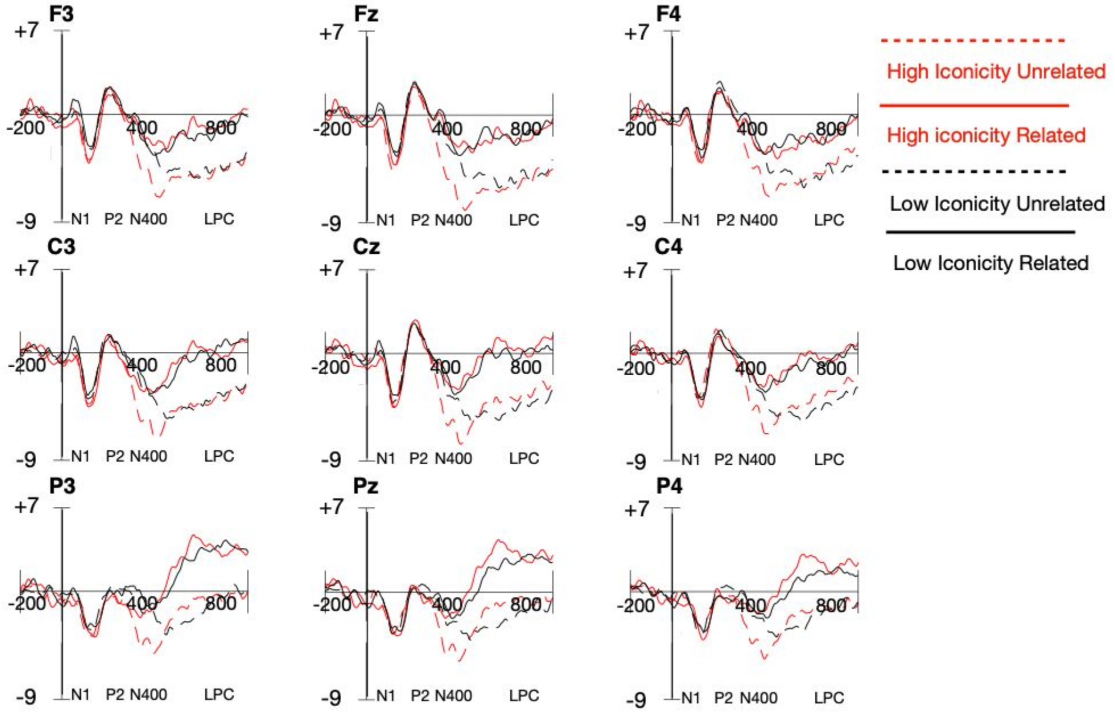

Figure 2. ERP plot of iconicity * relatedness in N1, P2, N400, and LPC. The continuous variable iconicity was split into high and low iconicity categories for illustration only, each containing 30% highest and lowest iconicity words. The plot was additionally filtered with 30Hz low pass filter for illustration.

<u>N1 (100-200ms)</u>

The first analysis suggested that unrelated items elicited more positive N1 ($\text{ß}_{\text{unrelated}}$=0.03, p<.001). Moreover, the comparison of the models with and without interaction terms was significant (p=.004). Follow-up analyses showed that the relatedness effect was significant for both onomatopoeia (p<.001) as well as other arbitrary words (p<.001), but not for sound related words (p=.67). The negativity was more central-parietal distributed, as the frontal electrodes were less positive ($\text{ß}_{\text{frontal}}$=0.04, p=.007). In the second analysis, we did not find the same effect of relatedness ($\text{ß}_{\text{unrelated}}$=0.04, p=0.15) or interaction between iconicity and relatedness ($\text{ß}_{\text{unrelated:iconicity}}$=0.01, p=0.56), but we found a significant effect of reaction time (ß=-0.03, p=.006). See full results and scalp distribution in Tables 5 to 7 and Figures 1 and 2, Supplementary Materials.

P2 (200-250ms)

There was a significant relatedness effect in the first analysis of the P2 time window: related items showed reduced positivity ($ß_{unrelated}$=0.02, p<.001). Duration also showed a significant effect (ß =-0.06, p=.006): longer words elicited less positive P2. There was no significant difference between models with and without interaction term. The effect was mostly frontal, with frontal electrodes being more positive than central ones ($ß_{frontal}$ =0.04, p=.004), and parietal electrodes were less positive than central ($ß_{parietal}$ =-0.17, p<.001). P2 was strongest along the midline of the scalp, as both left hemisphere electrodes ($ß_{left}$ =-0.05, p=.001) and right hemisphere electrodes ($ß_{right}$ =-0.042, p=.006) were less positive. The second analysis did not find any main or interaction effect involving relatedness or iconicity. With regards to control variables, P2 was less positive for words with longer reaction time (ß=-0.02, p=.02) and duration (ß=-0.07, p=.03). The effect was more central-frontal distributed ($ß_{parietal}$=-0.17, p<.001) compared with the frontal distribution in the initial analysis. But the effect was also strongest alone the midline, compared with both left hemisphere ($ß_{left}$=-0.06, p=.002) and right ($ß_{right}$=-0.04, p=.02). See full results in Tables 8 and9 and scalp distribution in Figures 3 and 4, Supplementary Materials.

N400 (300-500ms)

There was a significant main effect of relatedness ($ß_{unrelated}$=-0.06, p<.001) in the first analysis: unrelated pairs elicited a larger N400 than related pairs. Moreover, models' comparison showed a significant interaction (p < .001). The follow-up analysis showed that for related pairs, the three word types were not significantly different. However, for unrelated pairs, onomatopoeia were more negative than sound related words (p=.01) and other arbitrary words (p=.05). There was no significant difference between the two arbitrary word groups (p=.70).

The N400 effect was mostly central, as both frontal ($ß_{frontal}$ =0.05, p=.001) and parietal ($ß_{parietal}$ =0.08, p=.001) electrodes were less negative. The midline electrode was more negative than right hemisphere ($ß_{right}$ =0.03, p=.02), but not left hemisphere. This central-left distribution has been associated with auditory N400 (e.g. Hagoort and Brown, 2000).

We found a clear N400 effect also in the second analysis, such that related items were significantly less negative ($ß_{unrelated}$=-0.08, p=.001). There was also a significant interaction between relatedness and iconicity ($ß_{unrelated:iconicity}$=-0.04, p=.03): N400 in unrelated trials was more negative for words with higher iconicity, thus confirming the results from the first analysis. With regards to the control variables, items with longer RT also elicited more negative N400 (ß=-0.04, p<.001). This effect was strongest in the central frontal electrodes compared with parietal ($ß_{parietal}$=0.09, p<.001). See full results in Tables 10-12, and scalp distribution in Supplementary Materials. Figures 5 and 6.

LPC (600-900ms)

The first analysis found a significant main effect of relatedness ($ß_{unrelated}$ =-0.15, p<.001): related pairs showed more positive LPC than unrelated. Models' comparison showed a significant interaction (p=.02), but follow-up analysis did not find significant difference between conditions in either related or unrelated trials. We also found that words with longer RT showed less positive LPC (ß=-0.10, p<.001). The positivity increased from frontal to parietal areas, central being more positive than frontal ($ß_{frontal}$ =-0.10, p<.001), and parietal being more positive than central ($ß_{parietal}$ =0.20, p<.001). The effect was strongest in left hemisphere, as the left electrodes were more positive than the midline ($ß_{left}$ =0.04, p=.01), but midline and right electrodes were not significantly different.

The second analysis showed a significant main effect of relatedness ($ß_{related}$ =-0.17, p<.001), and a significant negative effect of RT (ß=-0.11, p<.001) in LPC. Frontal electrodes were less positive compared with central electrodes ($ß_{frontal}$ =-0.11, p<.001), while parietal electrodes were more positive ($ß_{parietal}$=0.21, p<.001). Left hemisphere was more positive ($ß_{left}$ =0.04, p=.04). See full results in Tables 13-15 and scalp distribution in Figures 7 and 8, Supplementary Materials.

Discussion

Vocal iconicity has been argued to play a critical role during language evolution (e.g., Perlmann et al., 2015), it has been found to support language acquisition (e.g., Laing, 2014), to render words more resistant after brain damage (Meteyard et al., 2015) and to facilitate processing also in healthy individuals (Sidhu et al., in press). It has also been shown that iconic words (onomatopoeia and mimetic words in Japanese) engage neural networks outside the typical language areas (to include right STS, Kanero et al., 2014).

However, the current electrophysiological literature provides mixed results with respect to whether and when different brain signatures are found for iconic vs. arbitrary words. We have argued that this may be due in part to the use of typologically different languages that can be more or less rich in iconicity; differences in the class of iconic words being investigated, and, finally, differences in the tasks used that may not always fully engage semantic processing. Here we focused on onomatopoeia, the most direct and imitative form of iconicity (as they do not require any cross-modal mapping which is typical instead of many cases of less direct iconicity as seen in mimetic words). Moreover, we focused on the semantic processing of these words using a task that explicitly required semantic processing (judging the semantic similarity between two words). Processing of onomatopoeia was compared to the processing of more arbitrary words which in a critical condition also referred to sound (e.g., *orchestra*). Words in the three word classes were carefully matched for a number of psycholinguistic dimensions.

Across both behavioural and EEG data, not surprisingly, we found strong effects of relatedness with related pairs being processed faster and eliciting a reduced N400. We did not find differences between onomatopoeic and arbitrary words in RTs and accuracy. This result replicates what was found by Peeters (2016) with onomatopoeia in Dutch in a lexical decision task. However, it should be noted that faster RTs (and more accurate responses) were reported in another study in English using onomatopoeia, also in a lexical decision task (Sidhu et al., in press). The reasons for this discrepancy are unclear as the languages are closely related, the three studies all focus on onomatopoeia and whereas we used a semantic judgements task, the other two studies both used lexical decision (auditory presentation in Peeters, 2016 and visual presentation in Sidhu et al., in press).

Importantly, in our study we found electrophysiological differences in processing across the three word types in the N400 time window (300-500ms). More specifically, we found that the ERP elicited by correctly rejecting non-semantically related pairs was more negative for the onomatopoeic words than for both sound-related and other arbitrary words. The time window and scalp distribution of the effect (maximal in centro-parietal electrodes) suggest that the effect is a genuine N400. The semantic processing of onomatopoeia, thus, seems to differ from more arbitrary words, even if these words belong to the same semantic field (words referring to sound), in line with previous findings from Dutch (Peeters, 2016). We also found a relatedness effect for N1 and P2, with unrelated pairs eliciting more positive ERP in both time windows but only in the analysis with iconicity as a categorical variable and not in the analysis with iconicity as continuous variable. Similarly, there was a significant interaction in

N1 between relatedness and iconicity but only in the analysis with iconicity as a categorical variable (word type). It is unclear why we found these effects, however, as we observed them only in the analysis with iconicity coded as categorical (and not as continuous variable), such effects could be driven by other (so far unknown) factors.

Finally, no effect was observed in the time-window for post-lexical (LPC: 600-900ms) processing driven by iconicity.

EEG signatures of iconicity

EEG studies investigating differences between onomatopoeic/mimetic words and arbitrary words, in principle, have the potential to identify differences in sensory, semantic and post-lexical processes and therefore provide a powerful tool to understand how iconic words are processed. With regards to sensory/phonological analysis of the words, we failed to observe consistent differences in early time windows, in contrast to previous studies. Lockwood and Tuomainen (2015) found differences between Japanese mimetic and arbitrary words in the peak of P2 (252-256ms). Peeters (2016) found differences in Dutch between onomatopoeia and arbitrary words in the N2 (150-200ms) time-window (which overlapped with our N1 time window). Lockwood and Tuomainen (2015) explained the larger P2 for mimetic words as linked to phonological differences between mimetic and other words in terms of, especially, reduplication of moras which is present in the mimetic but not in the other words considered in the study. Moreover, mimetic words are not restricted to auditory experience but they can refer to all sorts of sensory experience, thus the P2 effect might also be linked to multi-modal integration. In our study, we minimized any potential phonological difference between our onomatopoeic and control words and no multimodal integration was required for the onomatopoeic words (as well as for the sound-related arbitrary words). More difficult is to account for the difference in results between our study and the study by Peeters (2016).

Not only this study was on a much closer language (Dutch), but also just like in our study he focused on onomatopoeia and presented auditory single words. Peeters observed more negativity in 150-200ms for onomatopoeic than control words which he attributes to engagement of non-linguistic sound processing (in line with fMRI findings showing bilateral STS activations for mimetic words (Kanero et al., 2014). However, this explanation does not take into account that the fMRI findings refer to Japanese where there are important phonology-related differences for mimetics. An important difference between Peeters (2016) and our study is the task used. While Peeters used a lexical decision task, that may be argued to focus more on the form level, here we used a semantic decision task that forced participants to focus on semantics (and on the semantic relatedness between onomatopoeia and other words). This task was also a fair amount more difficult for our subjects, judging from their RTs (about twice as long as standard lexical decision RTs) and their error rates. One may speculate that lexical decision, by focusing more attention on wordform, may capture earlier correlates of iconicity (which indexes a transparent relation between wordform and meaning) than a task such as semantic decision which instead focuses attention of meaning only.

Importantly, we found a clear difference between onomatopoeic and arbitrary words in the N400 window. More specifically, we found a difference between onomatopoeic and arbitrary words from different semantic classes but also arbitrary words that, just like onomatopoeia, evoke sound-related experiences (e.g., *music*). It has been shown in fMRI studies that sound-related (arbitrary) words activate networks involved in auditory perception (including posterior STG/MTG, Kiefer et al., 2008; Kiefer et al., 2012) indicating how, in general, words evoke associated sensory experience, in line with embodiment views of semantic representation (Barsalou, 1999; Meteyard et al., 2012). Onomatopoeia and sound-related arbitrary words should evoke similar sensory experience, however, special to onomatopoeia is that such experience is part and parcel of the wordform. The larger N400 for onomatopoeia was observed in the unrelated condition which can be accounted for in terms of greater semantic activation for onomatopoeia that then leads to increased dissimilarity with the cue. There was no complementary increase in positivity for the related condition. As most of our cue-target pairs in the onomatopoeia condition were not related on the basis of sound, whereas most of the pairs in the sound-related arbitrary word condition were, the lack of an effect for related pairs might be due to the fact that any enhancement of semantic activation for sound-related features (assumed to be greater for onomatopoeia) is simply not relevant to the task as cue and target overlap in features other than sound (e.g., *fingers-clap*).

We did not observe any difference across word types in later time window (600-900ms, LPC), while, again we observed a strong effect of relatedness. As it is unclear the extent to which effects in this time window are genuine or carry-over effects from the N400 time window, and moreover, there is no clear prediction for differences across word type in this time window (which is considered to index post-lexical decision processes), this result will not be discussed further.

Proposed Mechanisms for Processing Onomatopoeia

There are few accounts of how iconicity effects might come about in language processing (for a review, see Sidhu and Pexman, 2017). Many of these accounts cover not just onomatopoeia but the more general associations between specific phonemes and some general semantic features (e.g., the association of ‘i’ with smallness) and are based on associative mechanisms that can pick up such statistical correspondences. However, onomatopoeia may be a special case. This is because they represent a unimodal type of iconicity (sounds in language mapping into sounds in the world); they are extremely simple mappings (imitative) that do not require much learning; they appear to be universal across world's languages and they feature heavily in the initial stages of language development. Onomatopoeia could be represented with both mediated as well as direct links between wordform and semantic (sensory-motor) features. In standard connectionist architectures for spoken word recognition (e.g., McClelland & Elman, 1986), it is assumed that the link between phonological and semantic features is mediated via intermediate representations. It is argued that this mediation is necessary precisely to implement arbitrary relationships that cannot, otherwise, be learnt. However, onomatopoeia could have, in addition to mediated links, also direct connections between phonological/phonetic and semantic features: those that map in an imitative manner between the two levels. This proposal is consistent with the results of the present study: activation of semantic features is enhanced and this, in turn, renders a mismatch with an unrelated cue more salient (hence a larger N400). This account is also in line with the developmental evidence reviewed in the introduction: direct mappings are easier to learn and therefore onomatopoeia should be the first words being learnt (Laing, 2014; Perry et al., 2018; Thompson et al., 2012). According to this view, direct links would develop for onomatopoeia and not for other iconic words. Compatible with this is the finding by Sidhu et al (in press) that facilitatory effects were found for onomatopoeia, regardless whether the task implicitly (lexical decision) or explicitly (phonological decision) recruited phonology, whereas facilitation was only found for other iconic words when the task explicitly recruited phonology.

A different mechanism that has been proposed in the literature for all iconic words (not just onomatopoeia), is that their lexical representation encompasses both linguistic and non-linguistic sensory (sound-related in the case of onomatopoeia) features. This account has been put forward by Kanero et al (2014) to account for bilateral activation of STS for mimetic but not arbitrary words. Our results can also be accounted for by this proposal.

However, it is worth noting that a traditional divide between the processing of linguistic sounds in the left and the processing of non-linguistic sounds in the right hemisphere has been challenged (see, e.g., Schirmer et al., 2012).

Conclusions

In the present paper, we have shown that making semantic judgements on onomatopoeic words vs. arbitrary words (including other words referring to sound) leads to processing differences as indexed by the N400. Crucially, by comparing the processing of onomatopoeia to a set of sound-related words, we could establish that any processing difference in this time window for the onomatopoeia cannot be accounted for in semantic terms only, but needs to take into account the special link between form and meaning that is present only in the onomatopoeia.

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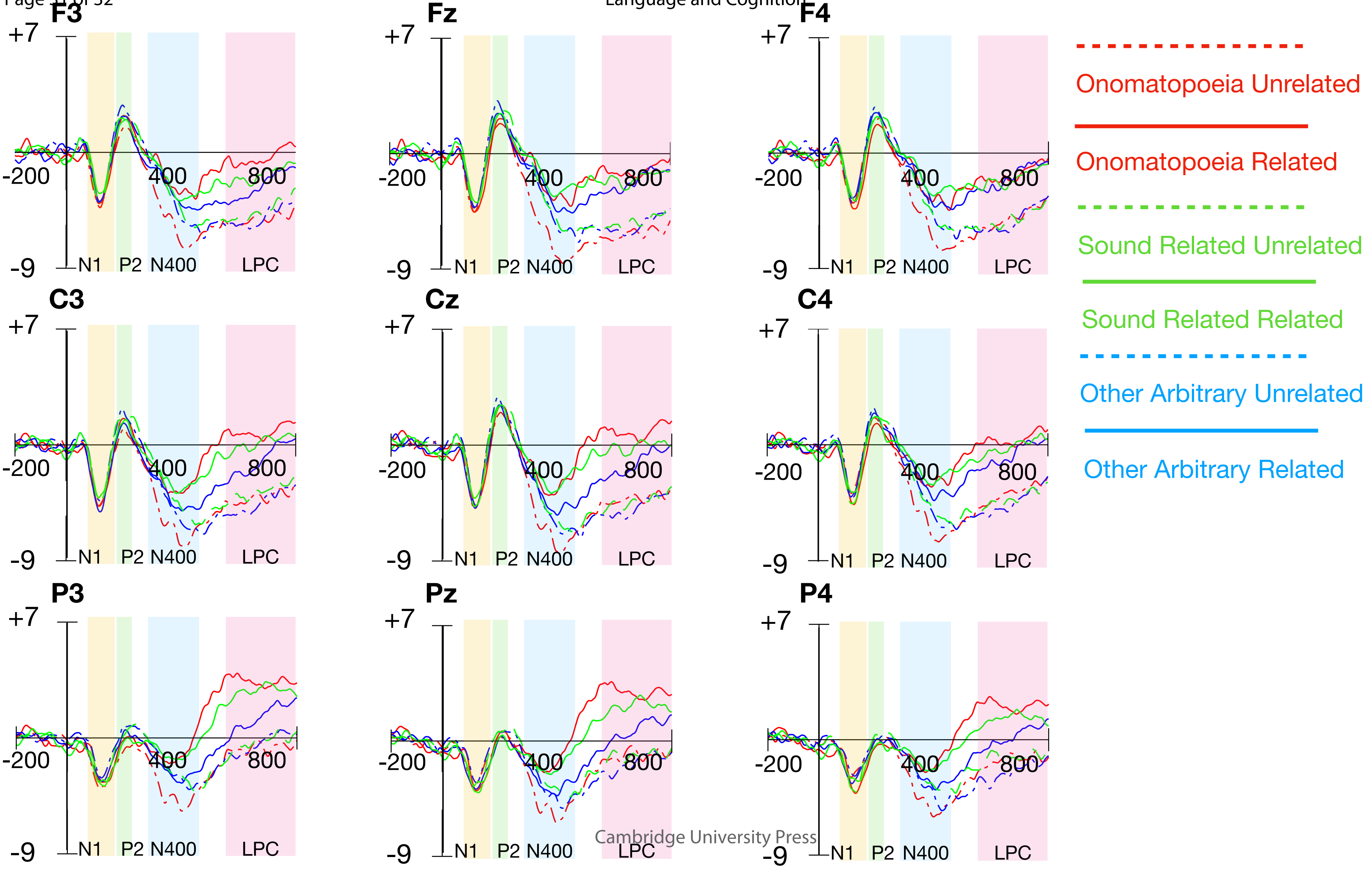
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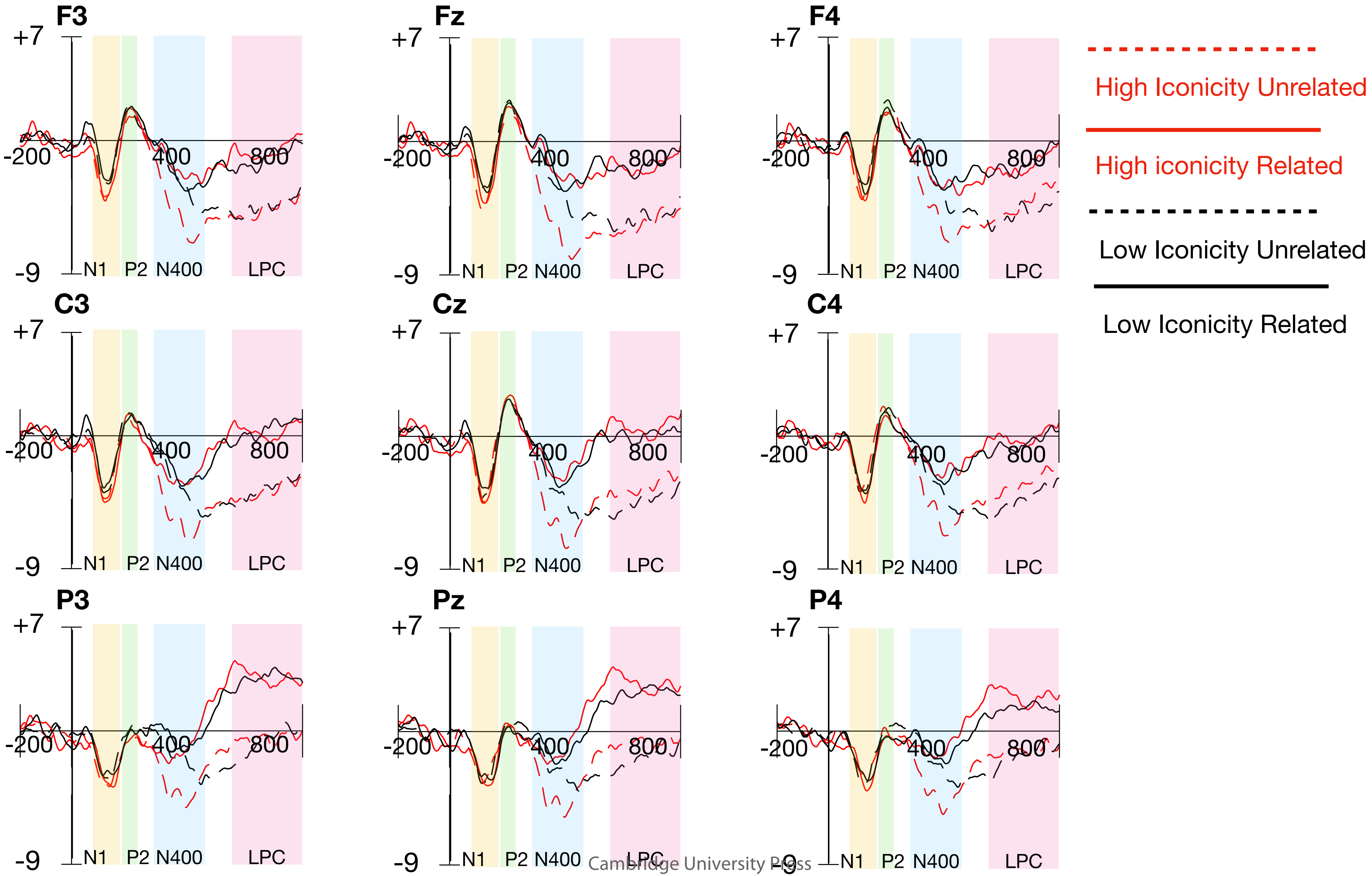
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