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1 **Electrophysiological signatures of English**
2 **onomatopoeia***

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24
25 **ABSTRACT**

26 Onomatopoeia is widespread across the world's languages. They represent
27 a relatively simple iconic mapping: the phonological/phonetic properties
28 of the word evokes acoustic related features of referents. Here, we explore
29 the EEG correlates of processing onomatopoeia in English. Participants
30 were presented with a written cue-word (e.g., *leash*) and then with a
31 spoken target-word. The target-word was either an onomatopoeia
32 (e.g., *bark*), a sound-related but arbitrary word (e.g., *melody*), or another
33 arbitrary word (e.g., *bike*). Participants judged whether the cue- and the
34 target-word were similar in meaning. We analysed Event-Related
35 Potentials (ERPs) in different time-windows: (i) early (100–200 and
36 200–250 ms) to assess differences in processing at the form-level; (ii) the
37 N400 time-window (300–500 ms) in order to establish if there are
38 differences in semantic processing across our word-types; and (iii) late
39 (600–900 ms) to assess post-lexical effects. We found that onomatopoeia

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1 differed from the other words in the N400 time-window: when cue and
 2 target were unrelated, onomatopoeic words led to greater negativity
 3 which can be accounted for in terms of enhanced semantic activation
 4 of onomatopoeia which leads to greater salience of the mismatch.
 5 We discuss results in the context of a growing body of literature
 6 investigating iconicity in language processing and development.

7 **KEYWORDS:** iconicity, onomatopoeia, EEG, ERP, N400, word processing.
 8
 9

AQ1 **1. Introduction**

11 In a paper entitled ‘The Origin of Speech’ (1960), Charles Hockett claimed
 12 that “in a semantic communicative system, the ties between meaningful
 13 message-elements and their meanings can be arbitrary or nonarbitrary.
 14 In language the ties are arbitrary. The word ‘salt’ is not salty nor granular;
 15 dog is not ‘canine’; ‘whale’ is a small word for a large object; ‘microorganism’
 AQ2 is the reverse” (1960, p. 6). However, as acknowledged by Hockett himself,
 17 if arbitrariness provides limitless possibilities to linguistic communication in
 18 terms of what can be communicated about, it also “has the disadvantage of
 AQ3 being arbitrary” (1960, p. 6). The lacking of an intrinsic connection between
 20 the phonological level and the semantic or conceptual level poses impediments,
 21 especially to lexical acquisition and processing: How can we effortlessly learn
 22 and use words when no hint to what they stand for is provided by their shape?
 23 And, why isn’t iconicity more widespread across languages? These and related
 24 questions are presently at the core of a growing number of studies that
 25 investigate iconicity and arbitrariness in language development and language
 26 processing (e.g., Lockwood & Dingemanse, 2015; Lupyan & Winter, 2018;
 27 Perniss, Thompson, & Vigliocco, 2010).

28 Non-arbitrary mappings are generally defined as ‘iconic’ – an ‘icon’ being
 29 “a sign which stands for something merely because it resembles it” (Peirce,
 30 1931–36, §3.362) – linguistic ‘iconicity’ being a sensory-perceived resemblance
 31 between properties of linguistic form and properties of meaning (Taub, 2001).
 32 Although traditionally dismissed as a marginal phenomenon in structural
 33 accounts of language (Chomsky, 1988; de Saussure, 1916; Hockett, 1960),
 34 iconicity plays a central role in recently developed research programmes
 35 grounded on embodied theories of human cognition (Meteyard, Cuadrado,
 36 Bahrami, & Vigliocco, 2012; Vigliocco, Perniss, & Vinson, 2014). Such
 37 programmes adopt a functional view of communication where arbitrariness
 38 and iconicity co-exist to facilitate learning and processing. Arbitrariness
 39 is assumed to allow for the efficient transmission of an unbounded array of
 40 concepts; iconicity is deemed instrumental in mapping language onto human
 41 experience as the content of linguistic communication. In particular, iconic
 42 mechanisms have been proposed to link lexical items to the cognitive

1 representation/re-enactment of the sensorimotor experience associated with
 2 real-world referents, thus facilitating the acquisition and processing of lexical
 3 meaning (Perniss & Vigliocco, 2014).
 4
 5

6 1.1. ICONICITY AND ONOMATOPOEIA IN LANGUAGES

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

17 In speech, a prominent form of iconicity is represented by onomatopoeia,
 18 i.e., lexical representations of acoustic events (e.g., *bubble*, *crash*, *tweet*, in
 19 English). Onomatopoeic words preserve in their form acoustic properties of
 20 the environmental sounds they copy. These iconic words tend to follow the
 21 phonotactic/phonological conventions of the language they belong to, hence,
 22 while a rooster in English-speaking countries would go *cock-a-doodle-doo*,
 23 a rooster in Italy would say *chicchirichi*. In addition to onomatopoeia, the
 24 amount of iconic material in lexica varies greatly (Berlin & O’Neill, 1981;
 25 Dingemanse, 2012; Jakobson & Waugh, 2002), with a number of languages
 26 outside the Indo-European family presenting recognizable sets of ‘ideophone’
 27 or ‘mimetic’ words (see Perniss et al., 2010 for a description). Indo-European
 28 languages like English do not have such a recognizable set of iconic words
 29 besides onomatopoeia; they do, however, have other forms of iconicity
 30 **AQ4** embedded in the lexicon, such as indirect iconicity (Sidhu & Pexman, 2017):
 31 e.g., the link between specific phonemes (e.g., /i/) and semantic features (e.g.,
 32 ‘small’). These types of indirect iconicity can be near universal: Blasi et al.
 33 **AQ5** (2016) compared the forms of 100 basic terms across 4,298 languages and
 34 found, in addition to other patterns, that words for the concept ‘small’ tended
 35 to include the high-front vowel /i/.

36 There is evidence that onomatopoeia and more generally iconic words may
 37 **AQ6** be easier to learn (e.g., Kantartzis, Imai, & Kita, 2011; Laing, 2014, 2019;
 38 Lockwood, Hagoort, & Dingemanse, 2016; Nygaard, Cook, & Namy, 2009).
 39 Evidence further suggests that onomatopoeic words are among the first words
 40 produced by babies. Laing (2014) showed that onomatopoeia made up the
 41 majority of early vocabulary for a German baby (< 12mo). Perry, Perlman,
 42 Winter, Massaro, and Lupyan (2018) showed that iconic words are used more

1 often by 10- to 26-month-old infants, and then their production decreases.
 2 Onomatopoeic words are also common in caregivers' language early on
 AQ7 and then decrease (Vigliocco et al., 2019). In sign language (British Sign
 4 Language, BSL) it has been found that more iconic signs are learnt before
 5 less iconic ones (Thompson, Vinson, Woll, & Vigliocco, 2012).

6 With regard to word processing, there is far less behavioural evidence
 7 supporting any advantage for onomatopoeic and generally iconic words.
 8 Meteyard, Stoppard, Snudden, Cappa, and Vigliocco (2015) showed that
 9 onomatopoeic words were better recognized as words than tightly matched
 10 arbitrary words by aphasic patients. While Peeters (2016) failed to observe
 11 any difference in lexical decisions for onomatopoeic and arbitrary words in
 12 Dutch, Sidhu, Vigliocco, and Pexman (in press), found a significant advantage
 13 for onomatopoeia in a visual lexical decision task as well as in a task that
 14 explicitly engaged phonology. In sign languages, there are now studies
 AQ8 spanning four different languages (BSL, ~~ASL, NGT and DGL~~) showing
 16 effects of iconicity on sign recognition using different paradigms (e.g., Grote &
 17 Linz, 2003; Ormel, Hermans, Knoors, & Verhoeven, 2009; Thompson,
 18 Vinson, & Vigliocco, 2009; Thompson et al., 2012; Vinson, Thompson,
 19 Skinner, & Vigliocco, 2015). Thus, we have limited results for onomatopoeia
 20 in different populations, tasks, and languages suggesting that any of these
 21 factors may affect whether facilitation is present.
 22
 23

24 1.2. ELECTROPHYSIOLOGICAL EVIDENCE FOR A DIFFERENT 25 STATUS OF ONOMATOPOEIA

26 Less than a handful of studies have considered the Event-Related Potentials
 27 (ERPs) elicited by iconic words (including onomatopoeia) so far, providing
 28 mixed results. Two studies reported difference between iconic and non-iconic
 29 words in early time-windows (Lockwood & Tuomainen, 2015; Peeters, 2016).
 30 In Lockwood and Tuomainen (2015), Japanese speakers were asked to read
 31 sentences in which a plausible or implausible target-word was either iconic
 32 (a mimetic/ideophone) or an arbitrary word. They found that the P2 component
 33 (252–256 ms) was more positive for the iconic words. As P2 is normally
 34 associated with phonological processing and multisensory integration, they
 35 inferred that the larger P2 was triggered by the combination of (1) the
 36 phonological processing of salient features of Japanese iconic words (e.g.,
 37 reduplication), and (2) multisensory integration between word form and
 38 sensory information associated with the mimetic words. In an auditory
 39 lexical decision task with Dutch speakers, Peeters (2016) found that an
 40 early component (N2, 150–200 ms) showed decreased negativity for
 41 onomatopoeia vs. arbitrary words, suggesting early processing differences
 AQ9 between onomatopoeia and other words. Finally, a study by Egashira,

1 Choi, Motoi, Nishimura, and Watanuki (2015), where iconic words were
2 auditorily presented to Japanese speakers, did not find any difference for
3 early components.

4 Results are equally mixed when considering the N400 component. Peeters
5 (2016) found that onomatopoeic words elicited less negative N400 (350–550 ms)
6 compared with arbitrary words, suggesting that iconicity may facilitate access
7 to semantic information. Less negative ERP around 400 ms for iconic words
8 was also found by Lockwood and Tuomainen (2015) and Egashira et al. (2015).
9 However, because of differences in temporal and spatial distribution, the
10 authors did not consider this component as N400. Finally, all three experiments
11 reported a difference for the Late Positive Complex (LPC), normally associated
12 with postlexical processing and metalinguistic decisions between onomatopoeic
13 and arbitrary words. Nevertheless, while Lockwood and Tuomainen (2015)
14 observed more positive LPC for iconic words between 400 and 800 ms, and
15 Peeters (2016) between 600 and 800 ms, Egashira et al. (2015) reported more
16 negative early LPC (200–500 ms) and middle LPC (500–900 ms) for
17 onomatopoeia vs. arbitrary words.

18 To sum up, the few available studies that have assessed neurophysiological
19 differences between processing iconic and less iconic words have provided
20 mixed results, which may have multiple causes. First, conflicting patterns may
21 come about as a consequence of cross-linguistic differences, as, for example,
22 Japanese mimetic words tend to have repeated moras, whereas this is not
23 necessarily the case for Dutch onomatopoeia. Second, the results may be due
24 to semantic differences between onomatopoeia and other iconic words used.
25 Onomatopoeia refers to sound; however, iconicity is not limited to the acoustic
26 dimension. We do not know whether this might matter. Finally, different
27 studies used different tasks that engage semantic processing to different extents.
28

30 1.3. THE PRESENT STUDY

31 Here, we focus on onomatopoeia in English. We use a clearly semantic
32 task and we provide a comparison between onomatopoeia and other, more
33 arbitrary, words also related to sound. We employed a semantic association
34 task where we asked participants to judge the relatedness between visually
35 presented words (cues) and spoken target words (onomatopoeic and arbitrary).
36 The semantic task was selected because we wanted to ensure that both
37 phonological features and semantic information were processed, so that
38 we can observe the full electrophysiological signature of onomatopoeia.
39 In contrast to previous experiments where lexical and sublexical differences
40 between onomatopoeic and control words were not carefully controlled, we
41 compared onomatopoeic words with two groups of arbitrary words: arbitrary
42 words from different semantic classes – matched on a large number of

1 psycholinguistic dimensions, but crucially also a group of arbitrary words
 2 that, just like onomatopoeic words, are rich in sensory features and that refer
 3 to sound (e.g., words like *music*). We included this third group to ensure that
 4 any difference in electrophysiological responses to the onomatopoeic words
 5 cannot be accounted for in terms of semantic differences between these words
 6 and control words, given that in embodied accounts all words referring to
 7 sound should activate sensory features relating to sound (see, e.g., Kiefer, Sim,
 8 Herrnberger, Grothe, & Hoenig, 2008). Moreover, in contrast to previous
 9 studies, we carefully matched onomatopoeic and arbitrary words for valence,
 10 as studies have found iconic words (especially mimetics in Japanese) to
 11 have more emotional associations than arbitrary words (Iwasaki, Vinson, &
 12 Vigliocco, 2007), and emotional valence has been shown to affect N2 and N400
 13 amplitude (e.g., Kanske & Kotz, 2007).

14 If onomatopoeic words involve direct mappings between phonological/
 15 phonetic features and semantic features (Vigliocco & Kita, 2006), or if they
 16 involve additional links from semantic to (multi)sensory areas (Kanero, Imai,
 17 Okuda, Okada, & Matsuda, 2014), we should observe differences in the N400
 18 component of the ERPs elicited by onomatopoeic vs. other words. Moreover,
 19 if any difference in the phonology of onomatopoeic and arbitrary words also
 20 have processing consequences, we should see differences in earlier time-
 21 windows, reflecting the sensory processing of the words. If onomatopoeic
 22 and arbitrary words differ in postlexical processing, we should see difference
 23 in LPC (600–900 ms).

26 **2. Method**

27 2.1. STIMULUS MATERIALS

28 Fifty target words were selected in each category (onomatopoeic, sound-
 29 related arbitrary; other arbitrary words). Stimuli were taken from materials
 30 used in previous studies investigating iconicity effects (Meteyard & Vigliocco,
 AQ11 2015) and for which information about their semantic properties was available
 32 (Brysbaert, Warriner, & Kuperman, 2014; Lynott et al., 2009, 2013; McRae
 AQ12 et al., 2005; Vinson & Vigliocco, 2008; see supplementary materials (available
 34 at <http://doi.org/10.1017/langcog.2019.38>), Table 16 for a full list of the
 35 stimuli). Across the three groups, words were matched for concreteness
 36 (Brysbaert et al., 2014), number of syllables, number of phonemes, number
 37 of letters, and log transformed frequency, orthographic neighbourhood
 38 density and phonological neighbourhood density generated from the
 39 English Lexicon Project’s HAL corpus (Balota et al., 2007). A one-way
 40 ANOVA confirmed that the three categories did not differ in any of these
 41 lexical features. For each word, we chose a related and an unrelated word
 42 to use as a cue (e.g., *leash/sad* for the target onomatopoeia *bark*; *chord/envy*

1 for the target sound-related word *melody*; *ride/history* for the target other
 2 arbitrary word *bike*).

3 An online norming study with 20 monolingual native British speakers was
 4 performed to ensure that the difficulty of the task was matched across word
 5 categories. Each participant was presented with either a related or unrelated
 6 cue and then the target word, and was asked to judge the relatedness by
 7 pressing ‘yes/no’ buttons on the screen as fast and as accurately as possible.
 8 ANOVAs showed that RTs and accuracy did not differ significantly across
 9 word-type conditions. However, unrelated pairs were significantly more
 10 accurate ($F(1,19) = 12.971, p = .002, \eta_p^2 = 0.406$) and required longer
 11 response time ($F(1,19) = 5.632, p = .028, \eta_p^2 = 0.229$) than related pairs.
 12 Based on these results, we also replaced one target word, 5 cues, and removed
 13 one target word, leaving 147 target words in total. It is important to note here
 14 that we did not control for whether the association between cue and target
 15 was related to sound or not. In our final list of items, most of the onomatopoeic
 16 words were not related in sound to the cue words (42/49); however, for the
 17 sound-related arbitrary words, 21/49 were related in sound. We avoided
 18 using onomatopoeic words as cue words; however, some of the cue words are
 19 iconic, according to available iconicity norms.¹ A female native speaker of
 20 British English produced the target words at a normal rate, recorded in a
 21 soundproof booth. The stereophonic stimuli had sampling frequency of
 22 44,100 Hz, and an intensity scale’s absolute peak normalized to 0.3 dB with
 23 Praat (v. 6.0.19.; Boersma, 2001) and duration between 450 and 900 ms.
 24
 25

26 2.2. PARTICIPANTS

27 Thirty-one native English speakers (mean age = 25) were recruited through
 28 the UCL Psychology Subject Pool. All participants were right-handed (assessed
 29 using the Edinburgh Handedness Inventory), with normal or corrected-to-
 30 normal vision, normal hearing, and without neurological disorders. Data from
 31 seven participants were excluded due to technical problems and/or accuracy
 32 below 80%. Twenty-four participants were included in the analysis (female = 11).
 33
 34

35 2.3. PROCEDURE

36 Participants were seated 100 cm in front of a computer in a shielded booth.
 37 The experiment was programmed with Presentation® software (Version 18.0,
 38 <www.neurobs.com>), with auditory stimuli presented through EEG-compatible
 39 headphones. Written instructions explained to participants that they would first
 40

41 [1] It was not possible to include iconicity of the cue as a control variable in the analyses
 42 because too many of our cue words do not have iconicity ratings in existing databases.

1 see a written word on the screen, then hear a word immediately afterwards,
 2 and their task was to judge whether the written word and the following
 3 spoken word were related in meaning. Participants were presented with 12
 4 practice trials before the experiment. Hand of response was counterbalanced
 5 across participants.

6 Two lists of stimuli were counterbalanced across participants, each containing
 7 147 target words and 49 fillers and correspondent cues (50% related and
 8 unrelated), so that no participant heard a target word twice. The stimuli were
 9 divided into six blocks, randomized within lists and across participants.

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

17 2.4. EEG RECORDING

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

27 The continuous EEG was referenced offline to the average of two mastoids
 28 and downsampled to 256 Hz. Due to the stimulus-onset asynchrony (SOA)
 29 in the target stimuli, the EEG waveform was timelocked to the actual onset of
 30 the word in the audio-recording, not the onset of recording. To do that, we
 31 annotated the SOA in each stimulus with Praat (v. 6.0.29.; Boersma, 2001),
 32 and edited the eventlists of each participant by adding SOA to the onset of
 33 the auditory stimuli using EEGLAB (v.14.1.1; Delorme & Makeig, 2004)
 34 and ERPLAB (v.7.0.0; Lopez-Calderon & Luck, 2014). EEG waveform was
 35 epoched from -200 to 900ms , corrected using -200 to 0 ms as baseline and
 36 filtered with 0.1 – 100Hz band-pass filter. Independent component analysis
 37 (ICA) (Chaumon, Bishop, & Busch, 2015) and artefact rejection was further
 38 performed to remove noise from the data (Mean = 11.088% , SD = 13.733
 39 across participants; rejection rate was similar across two relatedness levels
 40 and three word types). Based on previous literature (Egashira et al., 2015;
 41 Lockwood & Dingemans, 2015; Lockwood & Tuomainen, 2015; Peeters, 2016),
 42

1 we focused on N1 (100–200 ms), P2 (200–250 ms), N400 (300–500 ms), and
 2 LPC (600–900 ms) responses. The averaged ERP was calculated for those
 3 time intervals from 9 electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) (Luck,
 4 Vogel, & Shapiro, 1996). All of the components above are largest at midline
 5 (Fz, Cz, Pz). Adding the left- and right-side electrodes next to the electrodes
 6 above, provides a fair estimate of the scalp distribution on the anterior/
 7 posterior and laterality planes across the different conditions in our study.
 8 However, for completeness, we further carried out analyses including all
 9 electrodes (see supplementary materials).

12 2.5. DATA ANALYSIS

13 Linear mixed effect regression (LMER) analyses were performed for both
 14 behavioural and EEG data by participant and by item using the LME4 package
 15 (Bates, Maechler, Bolker, & Walker, 2015) in R version 3.4.1 (R studio team,
 AQ15 2016). For both behavioural and EEG data, two analyses were performed.
 17 In the first, we considered iconicity as a categorical variable and we contrasted
 18 three word types (onomatopoeic, sound-related arbitrary, and other arbitrary
 19 words). In the second, we considered iconicity as a continuous variable using
 20 ratings of iconicity collected by Lu, Healy, Binney, and Vigliocco (*in prep*).
 21 These ratings were obtained online in a survey in which 49 English speakers
 22 were asked to judge the iconicity of 320 words on a 1 (not iconic) to 7 (highly
 23 iconic) scale. Ratings were available for 47/49 onomatopoeic words and 33/49
 24 sound-related words. Thus, this secondary analysis excluded the other
 25 arbitrary words.

28 2.5.1. *Behavioural analysis*

29 We used LMER to analyse response time (RT) data (ms) and Logistic
 30 LMER for accuracy (0/1). The independent variables included word type
 31 (onomatopoeia, control, sound-related), relatedness (related, unrelated),
 AQ16 32 and relatedness*word type. Further, log frequency (van Heuven et al., 2014),
 33 age of acquisition (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012),
 34 concreteness (Brysbaert et al., 2014), and duration of stimulus were included
 35 as control variables. To capture by item and by participant variance, we
 36 included participant and word as random intercepts. All continuous variables
 37 were standardized. The significance of the critical interaction between
 38 relatedness and word type was established by comparing models with and
 39 without the interaction term using an ANOVA, which is a built-in function
 40 of R performing Wald chi-squared tests for LMER. Significant interactions
 41 were further analysed by comparing least square means using the emmeans
 42 package in R (Lenth, 2018).

TABLE 1. *RT's descriptive statistics (ms)*.

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

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 a model comparison. We further included in the random structure iconicity, relatedness, and iconicity*relatedness as a random slope.

2.5.2. 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: the RT of the trial, the mean accuracy of the item, and the electrode site. The electrode sites were coded as two variables, one for left/right (left = -1, centre = 0, right = 1), and one for frontal/parietal (frontal = -1, centre = 0, parietal = 1) (Emmorey, Midgley, Kohen, Sehyr, & Holcomb, 2017). All continuous variables were standardized. The significance of interactions was established as above. Only correct trials were analysed.

3. Results

3.1. BEHAVIOURAL RESULTS

3.1.1. RTs

The main LMER analysis found a significant main effect of relatedness ($\beta_{\text{unrelated}} = 0.07$, $p < .001$): judgement for related pairs was faster than for unrelated trials. There was also a significant main effect of duration ($\beta = 0.17$, $p < .001$): 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 a significant positive mean effect of duration ($\beta = 0.14$, $p < .001$) on mean RT. But the relatedness effect was not significant. No other significant effect was found. See Tables 1 and 2 in the Supplementary Materials for full results.

TABLE 2. *Accuracy's descriptive statistics*

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

3.1.2. Accuracy

In the first binary logistic regression, we found a significant main effect of relatedness ($\beta_{\text{unrelated}} = 0.72, p < .001$): 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 ($\beta_{\text{unrelated}} = 0.77, p < .001$) was also found in the second analysis, showing a consistent effect. No other main effect or interaction were significant. See Tables 3 and 4, supplementary materials, for full results.

3.2. 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 a predictor.

3.2.1. N1 (100–200 ms)

The first analysis suggested that unrelated items elicited more positive N1 ($\beta_{\text{unrelated}} = 0.03, p < .001$). 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 onomatopoeic ($p < .001$) as well as for 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 ($\beta_{\text{frontal}} = 0.04, p = .007$). In the second analysis, we did not find the same effect of relatedness ($\beta_{\text{unrelated}} = 0.04, p = .15$) or interaction between iconicity and relatedness ($\beta_{\text{unrelated:iconicity}} = 0.01, p = .56$), but we found a significant effect of reaction time ($\beta = -0.03, p = .006$). See full results and scalp distribution in Tables 5 to 7 and Figures 1 and 2, in the supplementary materials.

3.2.2. P2 (200–250 ms)

There was a significant relatedness effect in the first analysis of the P2 time-window: related items showed reduced positivity ($\beta_{\text{unrelated}} = 0.02, p < .001$).

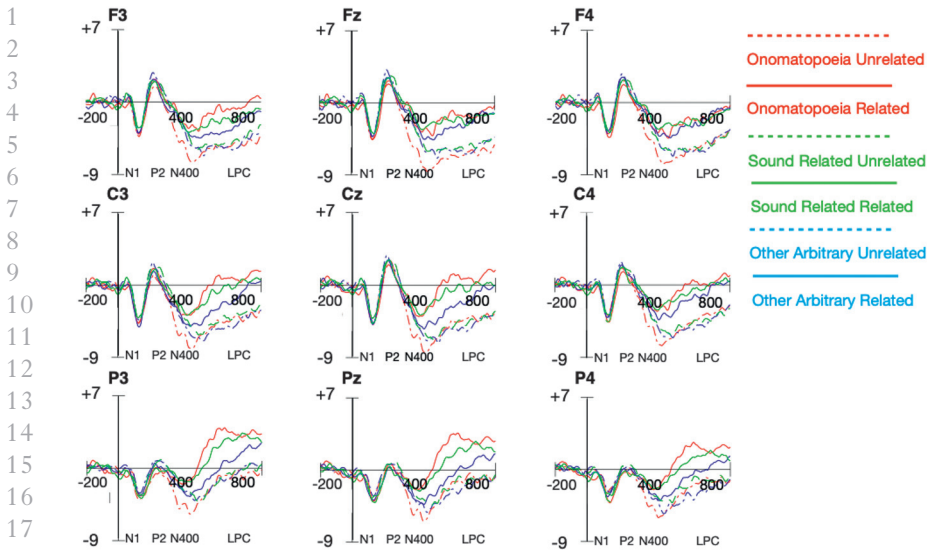


Fig. 1. ERP plot of word type*relatedness in N1, P2, N400, and LPC. The plot was additionally filtered with a 30Hz low-pass filter for illustration. (Colour online)

Duration also showed a significant effect ($\beta = -0.06$, $p = .006$): longer words elicited less positive P2. There was no significant difference between models with and without the interaction term. The effect was mostly frontal, with frontal electrodes being more positive than central ones ($\beta_{\text{frontal}} = 0.04$, $p = .004$), and parietal electrodes were less positive than central ($\beta_{\text{parietal}} = -0.17$, $p < .001$). P2 was strongest along the midline of the scalp, as both left-hemisphere electrodes ($\beta_{\text{left}} = -0.05$, $p = .001$) and right-hemisphere electrodes ($\beta_{\text{right}} = -0.042$, $p = .006$) were less positive. The second analysis did not find any main or interaction effect involving relatedness or iconicity. With regard to control variables, P2 was less positive for words with a longer reaction time ($\beta = -0.02$, $p = .02$) and duration ($\beta = -0.07$, $p = .03$). The effect was more central-frontal distributed ($\beta_{\text{parietal}} = -0.17$, $p < .001$) compared with the frontal distribution in the initial analysis. But the effect was also strongest along the midline, compared with both left hemisphere ($\beta_{\text{left}} = -0.06$, $p = .002$) and right ($\beta_{\text{right}} = -0.04$, $p = .02$). See full results in Tables 8 and 9 and scalp distribution in Figures 3 and 4, in the supplementary materials.

3.2.3. N400 (300–500 ms)

There was a significant main effect of relatedness ($\beta_{\text{unrelated}} = -0.06$, $p < .001$) in the first analysis: unrelated pairs elicited a larger N400 than related pairs. Moreover, a models' comparison showed a significant interaction ($p < .001$).

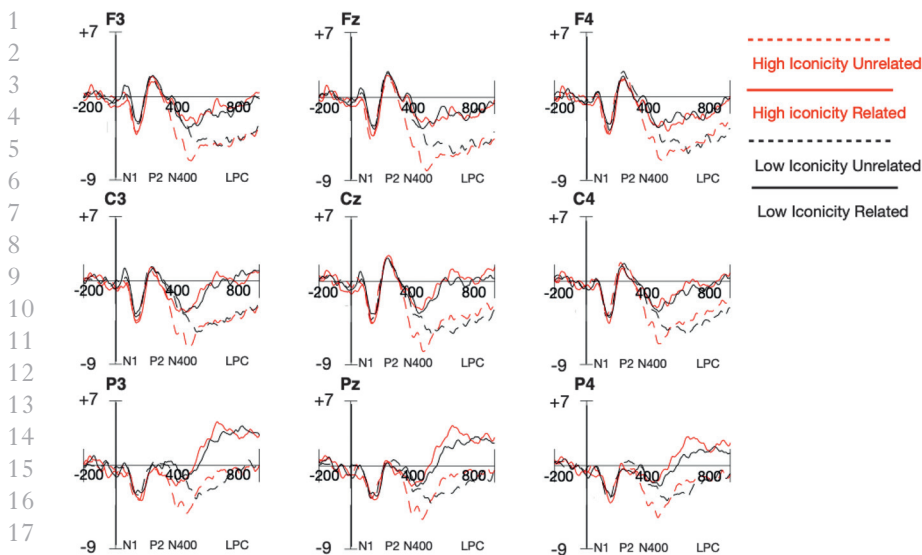


Fig. 2. ERP plot of iconicity*relatedness in N1, P2, N400, and LPC. The continuous variable iconicity was split into high and low iconicity categories for illustration only, each containing 30% highest and lowest iconicity words. The plot was additionally filtered with a 30Hz low-pass filter for illustration.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

The follow-up analysis showed that, for related pairs, the three word types were not significantly different. However, for unrelated pairs, onomatopoeic words 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 ($\beta_{\text{frontal}} = 0.05, p = .001$) and parietal ($\beta_{\text{parietal}} = 0.08, p = .001$) electrodes were less negative. The midline electrode was more negative than right hemisphere ($\beta_{\text{right}} = 0.03, p = .02$), but not the left hemisphere. This central-left distribution has been associated with auditory N400 (e.g., Hagoort & Brown, 2000).

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

3.2.4. LPC (600–900 ms)

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

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

4. Discussion

Vocal iconicity has been argued to play a critical role during language evolution (e.g., Perlman, Dale, & Lupyan, 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 (onomatopoeic and mimetic words in Japanese) engage neural networks outside the typical language areas (to include right STS; Kanero et al., 2014).

However, the current electro-physiological 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 it does 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). The processing of onomatopoeic words 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 judgement 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 electro-physiological differences in processing across the three word types in the N400 time-window (300–500 ms). 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 onomatopoeic words, 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 a continuous variable), such effects could be driven by other (so far unknown) factors.

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

4.1. 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 postlexical processes and therefore provide a powerful tool for understanding how iconic words are processed. With regard to the sensory/phonological analysis of the words, we failed to observe consistent

1 differences in early time-windows, in contrast to previous studies. Lockwood
 2 and Tuomainen (2015) found differences between Japanese mimetic and
 3 arbitrary words in the peak of P2 (252–256 ms). Peeters (2016) found differences
 4 in Dutch between onomatopoeic and arbitrary words in the N2 (150–200 ms)
 5 time-window (which overlapped with our N1 time-window). Lockwood and
 6 Tuomainen (2015) explained the larger P2 for mimetic words as linked to
 7 phonological differences between mimetic and other words in terms of,
 8 especially, the reduplication of moras which is present in the mimetic but not
 9 in the other words considered in the study. Moreover, mimetic words are
 10 not restricted to auditory experience but can refer to all sorts of sensory
 11 experience, thus the P2 effect might also be linked to multimodal integration.
 12 In our study, we minimized any potential phonological difference between
 13 our onomatopoeic and control words, and no multimodal integration was
 14 required for the onomatopoeic words (as well as for the sound-related
 15 arbitrary words). More difficult is to account for the difference in results
 16 between our study and the study by Peeters (2016). Not only was this study
 17 on a much closer language (Dutch), but also, just as in our study, he focused
 18 on onomatopoeia and presented auditory single words. Peeters observed
 19 more negativity in 150–200 ms for onomatopoeic than control words, which
 20 he attributes to the engagement of non-linguistic sound processing (in line
 21 with fMRI findings showing bilateral STS activations for mimetic words
 22 (Kanero et al., 2014). However, this explanation does not take into account
 23 the fact that the fMRI findings refer to Japanese, where there are important
 24 phonology-related differences for mimetics. An important difference between
 25 Peeters (2016) and our study is the task used. While Peeters used a lexical
 26 decision task, that may be argued to focus more on the form level; here we
 27 used a semantic decision task that forced participants to focus on semantics
 28 (and on the semantic relatedness between onomatopoeic and other words).
 29 This task was also a bit more difficult for our subjects, judging from their RTs
 30 (about twice as long as standard lexical decision RTs) and their error rates.
 31 One may speculate that lexical decision, by focusing more attention on word-
 32 form, may capture earlier correlates of iconicity (which indexes a transparent
 33 relation between word-form and meaning) than a task such as semantic
 34 decision, which instead focuses attention of meaning only.

35 Importantly, we found a clear difference between onomatopoeic and arbitrary
 36 words in the N400 window. More specifically, we found a difference between
 37 onomatopoeic and arbitrary words from different semantic classes, but also
 38 arbitrary words that, just like the onomatopoeic ones, evoke sound-related
 39 experiences (e.g., *music*). It has been shown in fMRI studies that sound-
 40 related (arbitrary) words activate networks involved in auditory perception
 AQ18 (including posterior STG/MTG; Kiefer et al., 2008; Kiefer et al., 2012),
 42 indicating how, in general, words evoke associated sensory experience, in line

1 with embodiment views of semantic representation (Barsalou, 1999; Meteyard
 2 et al., 2012). Onomatopoeic and sound-related arbitrary words should evoke
 3 similar sensory experience; however, special to onomatopoeic words is that
 4 such experience is part and parcel of the word-form. The larger N400 for
 5 onomatopoeic words was observed in the unrelated condition, which can
 6 be accounted for in terms of greater semantic activation for onomatopoeic
 7 words that then leads to increased dissimilarity with the cue. There was no
 8 complementary increase in positivity for the related condition. As most of
 9 our cue–target pairs in the onomatopoeic condition were not related on the
 10 basis of sound, whereas most of the pairs in the sound-related arbitrary word
 11 condition were, the lack of an effect for related pairs might be due to the fact
 12 that any enhancement of semantic activation for sound-related features
 13 (assumed to be greater for onomatopoeic words) is simply not relevant
 14 to the task as cue and target overlap in features other than sound (e.g.,
 15 *fingers–clap*).

16 We did not observe any difference across word types in later time-window
 17 (600–900 ms, LPC), while, again we observed a strong effect of relatedness.
 18 As it is unclear whether the extent to which effects in this time-window are
 19 genuine or carry-over effects from the N400 time-window, and, moreover,
 20 there is no clear prediction for differences across word type in this time-
 21 window (which is considered to index postlexical decision processes), this
 22 result will not be discussed further.

25 4.2. PROPOSED MECHANISMS FOR PROCESSING ONOMATOPOEIA

26 There are few accounts of how iconicity effects might come about in language
 AQ19 27 processing (for a review, see Sidhu & Pexman, 2017). Many of these accounts
 28 cover not just onomatopoeia but the more general associations between specific
 29 phonemes and some general semantic features (e.g., the association of ‘i’ with
 30 smallness) and are based on associative mechanisms that can pick up such
 31 statistical correspondences. However, onomatopoeic words may be a special
 32 case. This is because they represent a unimodal type of iconicity (sounds in
 33 language mapping onto sounds in the world); they are extremely simple
 34 mappings (imitative) that do not require much learning; they appear to be
 35 universal across the world’s languages; and they feature heavily in the initial
 36 stages of language development.

37 Onomatopoeic words could be represented with mediated as well as direct
 38 links between word-form and semantic (sensorimotor) features. In standard
 39 connectionist architectures for spoken word recognition (e.g., McClelland &
 40 Elman, 1986), it is assumed that the link between phonological and semantic
 41 features is mediated via intermediate representations. It is argued that this
 42 mediation is necessary precisely to implement arbitrary relationships that

1 cannot, otherwise, be learnt. However, onomatopoeia could have, in addition
2 to mediated links, also direct connections between phonological/phonetic and
3 semantic features: those that map in an imitative manner between the two
4 levels. This proposal is consistent with the results of the present study:
5 activation of semantic features is enhanced and this, in turn, renders a
6 mismatch with an unrelated cue more salient (hence a larger N400). This
7 account is also in line with the developmental evidence reviewed in the
8 ‘Introduction’: direct mappings are easier to learn and therefore onomatopoeic
9 words should be the first words being learnt (Laing, 2014; Perry et al., 2018;
10 Thompson et al., 2012). According to this view, direct links would develop
11 for onomatopoeic and not for other iconic words. Compatible with this is
12 the finding by Sidhu et al. (in press) that facilitatory effects were found for
13 onomatopoeic words, regardless of whether the task implicitly (lexical
14 decision) or explicitly (phonological decision) recruited phonology, whereas
15 facilitation was only found for other iconic words when the task explicitly
16 recruited phonology.

17 A different mechanism that has been proposed in the literature for all
18 iconic words (not just onomatopoeic words), is that their lexical representation
19 encompasses both linguistic and non-linguistic sensory (sound-related in the
20 case of onomatopoeia) features. This account has been put forward by Kanero
21 et al. (2014) to account for bilateral activation of STS for mimetic but not
22 arbitrary words. Our results can also be accounted for by this proposal.
23 However, it is worth noting that a traditional divide between the processing
24 of linguistic sounds in the left and the processing of non-linguistic sounds
25 in the right hemisphere has been challenged (see, e.g., Schirmer, Fox, &
26 Grandjean, 2012).

27 28 29 4.3. CONCLUSIONS

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

38 39 40 **Supplementary materials**

41 For supplementary materials for this paper, please visit <[http://doi.org/10.1017/
42 langcog.2019.38](http://doi.org/10.1017/langcog.2019.38)>.

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