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Electrophysiological evidence for the morpheme-based combinatoric processing of English compounds

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Abstract

The extent to which the processing of compounds (e.g., “catfish”) makes recourse to morphological-level representations remains a matter of debate. Moreover, positing a morpheme-level route to complex word recognition entails not only access to morphological constituents, but also combinatoric processes operating on the constituent representations; however, the neurophysiological mechanisms subserving decomposition, and in particular morpheme combination, have yet to be fully elucidated. The current study presents electrophysiological evidence for the morpheme-based processing of both lexicalized (e.g., “teacup”) and novel (e.g., “tombnote”) visually-presented English compounds; these brain responses appear prior to and are dissociable from the eventual overt lexical decision response. The electrophysiological results reveal increased negativities for conditions with compound structure, including effects shared by lexicalized and novel compounds, as well as effects unique to each compound type, which may be related to aspects of morpheme combination. These findings support models positing across-the-board morphological decomposition, counter to models proposing that putatively complex words are primarily or solely processed as undecomposed representations, and motivate further electrophysiological research toward a more precise characterization of the nature and neurophysiological instantiation of complex word recognition.

Keywords

compound words; lexical access; lexical decision; morphology; EEG

INTRODUCTION

The extent to which the representation and processing of complex words such as compounds (e.g., *teacup*) makes recourse to morpheme-level units remains a matter of debate. Alternative approaches range from full-decomposition models, in which complex word recognition involves morpheme-based processing in the general case (e.g., Stockall & Marantz, 2006; Taft, 2004), to approaches which posit atomic, whole-word representations or subsymbolic non-morphological representations (e.g., Butterworth, 1983; Bybee, 1995; Kuperman, 2013; McClelland & Patterson, 2002; Seidenberg & Gonnerman, 2000), to dual-

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route models in which both morpheme-level and whole-word processing routes are posited (e.g., Pinker, 1999; Clahsen, 1999). Adjudicating among these alternatives is crucial, as these approaches make fundamentally distinct claims regarding what the basic-level unit of lexical knowledge is, and distinct assumptions regarding the nature of linguistic (and other mental) representations and computations more broadly (e.g., Pinker, 1999; Rumelhart & McClelland, 1986). While there is now considerable evidence suggesting that morpheme-level representations are activated during complex word processing, broadly consistent with decompositional approaches, the positing of a morpheme-based route to complex word recognition entails mechanisms for segmenting putatively complex words to identify candidate constituents, the activation of these constituents from memory, and mechanisms for combining these morphemes to form and interpret the complex word. Relatively little is known, however, regarding the cognitive and neural mechanisms subserving these aspects of complex word processing (e.g., Marslen-Wilson & Tyler, 2007). In the current study, we address these issues, adopting the processing of visually-presented lexicalized and novel compounds in English as our test case. We present new behavioral and neural evidence demonstrating the activation of constituent morphemes for both lexicalized and novel compounds during visual word recognition; crucially, we also identify dissociable neurophysiological and behavioral responses which we propose may reflect the post-decompositional processing of morpheme combinations.

As noted above, there is now considerable evidence suggesting early, automatic access to constituent representations in putatively complex words. In particular, the psycholinguistic technique masked priming has become a primary method for demonstrating early, automatic decomposition (see Rastle & Davis, 2008, for a review). For example, Rastle, Davis and New (2004) showed significant, equivalent priming for truly morphologically related prime target pairs (e.g., *hunter-hunt*) and for merely apparently morphologically related prime-target pairs (e.g., *corner-corn*), while orthographic overlap by itself did not yield similar priming (e.g., *brothel-broth*). These results suggest initial morphological-level segmentation and activation whenever a word is potentially segmentable into constituents, even when such an analysis is ultimately incorrect (as the robust priming for the apparent morphological relatedness condition shows). While most of this research has focused on affixed forms or other formally regular morphological operations, Fiorentino and Fund-Reznicek (2009) showed significant and equivalent masked priming effects for transparent compounds and their constituents (e.g., *teacup-tea* and *teacup-cup*) and opaque compounds and their constituents (e.g., *honeymoon-honey* and *honeymoon-moon*), while orthographic overlap did not yield such priming (e.g., *penguin-pen* and *platform-form*). These findings are consistent with full decomposition models, in which word forms are initially segmented at the morphological level in the general case (e.g., Stockall et al., 2006; Taft, 2004). Compounding provides a particularly useful test case here, since English compounds do not carry any affix or other formally regular reflex of word formation; thus, evidence from compounding underscores that morphological decomposition is not dependent on the presence of an affix to quickly “strip” in order to facilitate rapid decomposition (cf., Taft & Forster, 1975; for a recent discussion of the potential roles of other types of segmentation cue in compound processing, see Hyönä, 2012). Converging psycholinguistic evidence for decomposition in compounds also comes from overt priming tasks (e.g., Libben, Gibson,

Yoon, & Sandra, 2003; Zwitserlood, 1994), production (e.g., Bien, Levelt, and Baayen, 2005), eye-tracking (e.g., Pollatsek & Hyönä, 2005; Frisson, Niswander-Klement, & Pollatsek, 2008), and lexical decision (e.g., Andrews, 1986; Duñabeitia, Perea, & Carreiras, 2007; Juhasz, Starr, Inhoff, & Placke, 2003; Libben et al., 2003; Ji, Gagné, & Spalding, 2011, among others); see Semenza and Mondini (2010) for a review of aphasiological evidence supporting the morpheme-based processing of compounds.

As compounding is a productive word formation operation in many languages including English, and since the meanings of compounds show wide variation in semantic transparency, compounding provides a particularly useful domain for examining the scope of morpheme-based processing and for probing the combinatoric processes associated with complex word recognition (e.g., Libben, 2006). Indeed, compound processing has been the focus of several recent studies examining the neural instantiation of complex word recognition, primarily using electrophysiological techniques (EEG, MEG), expanding the range of findings informing neurocognitive models of complex word beyond inflection and derivation (e.g., Pinker & Ullman, 2002, Marslen-Wilson & Tyler, 2007). With electrophysiology, it is possible to track the processing of complex words previous to, and potentially independent of, any overt behavioral response, providing a new wedge into debates regarding the role of morphemes in complex word recognition, toward identifying brain mechanisms linked to the decomposition and combination of morphemes. Thus, electrophysiological research in compounding carries the potential to increase our understanding of how linguistic representations and combinatoric operations are instantiated in the brain.

A primary component associated with morpheme activation and combination in the EEG literature is the N400. The N400 is a negative-going component typically emerging around 300–500 ms post-onset of a visually or auditorily presented word, and is sensitive to a number of lexical factors such as word frequency, priming, and lexicality (Kutas & Federmeier, 2000, 2011). The extent to which N400 reflects integrative, semantic processing of incoming words, beyond any effects of lexical variables or lexical expectations engendered by the previous context, remains at issue (e.g., Lau, Phillips, & Poeppel, 2008). As regards complex word recognition, McKinnon, Allen, and Osterhout (2003), for example, compared responses to known words with non-productive, bound roots, novel words formed from illicit combinations of affixes and bound roots, and words and nonwords without bound roots. McKinnon et al. (2003) found a lexicality effect for the nonwords without bound roots, but the lexicalized and novel words formed by root-affix combinations did not differ in N400. McKinnon et al. (2003) argue that these results implicate morphological decomposition, even for these non-productive morphemes, since the two complex conditions patterned alike, but differed from the unstructured nonwords. They further speculate that evidence for an increased N400 due to composition is lacking in their study since a compositional meaning cannot be generated from these bound roots. Janssen, Wiese, and Schlesewsky (2006) report N400-like effects for the incorrect application of suffixes to German derived words. Root-affix mismatches involving a violation of the word-class selectional requirement of the affix yielded a larger and broader N400 than did violations which involved prosodic rather than word-class mismatches. These results, together with a series of studies implicating N400 in morphological priming paradigms (e.g.,

Lavric, Clapp, & Rastle, 2007; Lavric, Rastle, & Clapp, 2011; Morris, Frank, Grainger, & Holcomb, 2007; Royle, Drury, Bourguignon, & Steinhauer, 2012), implicate N400 as a component of interest for detecting morphological activation.

Several EEG studies on compounds engage issues regarding to what extent complex word recognition involves morphological decomposition and composition, and what neurophysiological mechanisms subserve these computations. Much of the EEG research has focused on the auditory processing of compounds, with evidence put forth for the decomposition of auditory compounds into constituents, and some suggestive evidence for components potentially linked to the integration of constituents to compose complex meanings. For example, Holle, Gunter, and Koester (2010) also examined the processing of auditorily-presented German compounds, testing word-word compounds, novel stimuli with an existing morpheme in final position and nonce initial constituent, stimuli with a word-initial morpheme and nonce final constituent, and novel stimuli fully composed of nonce constituents. All stimuli were presented with compound prosody. Holle et al. (2010) observed an increased N400 for nonce initial constituents vs. existing constituents, attributed to the attempted lexical access of the initial constituent, and, interestingly, also found a broad N400 effect which was larger for the existing head constituent when preceded by a nonce initial constituent than when it was preceded by an existing initial constituent, which is taken to suggest that N400 reflects, in part, the attempted integration of constituents, rather than solely the access to constituents. Likewise, Koester, Gunter, and Wagner (2007) tested auditorily presented, low-frequency semantically transparent vs. opaque German compounds, finding that semantic transparency modulates an N400-like response; this negativity was greater for the transparent than the opaque compounds. They interpret this as reflecting increased processing of the transparent compared to the opaque compounds, for which they speculate composition may not be attempted (see also Koester, Holle, and Gunter, 2009, for increased negativities to less-plausible constituents in the processing of auditory trimorphemic compounds).

Likewise, Bai, Bornkessel-Schlesewsky, Wang, Hung, Schlesewsky, and Burkhardt (2008) tested Chinese compounds presented auditorily with compound prosody, manipulating semantic transparency (more specifically, the semantic relatedness of the non-head and head constituents) and the syntactic category of the compound constituents. Bai et al. (2008) report an increased negativity in a 300–600 ms time window for the head constituent for compounds with semantically distinct constituents, which they take as evidence for an N400 effect of reinterpretation following an incorrect semantic prediction generated based on hearing the first constituent (though not for unexpected syntactic categories).

The results from Bai et al. (2008), and those summarized above for German compounds, provide cross-linguistic evidence that is broadly consistent in suggesting decompositional and compositional processing of auditorily-presented compounds bearing compound prosody, as they unfold in real time. Moreover, these studies suggest that constituent access (Holle et al., 2010) and compositional processing may engender N400 effects (Holle et al., 2010; Koester et al., 2007, 2009; Bai et al., 2008). These studies thus converge in suggesting that N400-like negativities may indeed reflect aspects of morphological decomposition and post-decompositional, combinatoric operations. In the studies that follow, we discuss

evidence for decompositional and compositional processing in visually-presented compounds. Visually-presented compounds provide an important test case for probing the extent to which compound processing makes recourse to morphological decomposition and composition, since in visually-presented compounds, the morphemes are presented simultaneously, rather than unfolding over time as in the auditory signal; likewise, they do not carry prosodic cues to their structure.

Studies on the decomposition and composition of visually-presented compounds, are however, relatively few in number. Krott, Baayen, and Hagoort (2006) examined EEG responses to Dutch lexicalized compounds, manipulating whether the interfix (the linking element between constituents in Dutch compounds) is correct or incorrect, and whether the interfix in novel compounds is supported or unsupported by analogy to similar, known forms. They also included both grammatical and ungrammatical plural marking on the compounds, to compare violations of regular inflection (pluralization) and analogy-based interfixation processing. The primary focus of that study is on the LAN, a component that has been associated with morphosyntactic processing in sentential context (e.g., Friederici, 1995 among others; cf. Kluender & Kutas, 1993, and Vos, Gunter, Herman, Kolk, & Mulder, 2001 for alternative interpretations that do not focus on morphosyntax *per se*, and see Krott et al., 2006 for discussion of the varying scalp distribution of effects classified as the LAN across studies) and with morphological-level violations within complex words.

The results of this study, which utilized a passive reading design, show a LAN for the plural suffix manipulation, and an effect of the interfix manipulation in anterior regions for existing compounds, but not for the novel compounds (see also Koester, Gunter, Wagner, and Friederici, 2004 for LAN elicitation in a gender agreement violation paradigm testing German compounds). A broad negativity was also noted for the novel compounds beginning around 350 ms; the authors discuss both lexicality and lower-frequency first constituents (as they were not able to match the existing and novel compounds on that property) as potential origins for this effect. The Krott et al. (2006) study suggests that LAN-like anterior negativities may reflect aspects of morphosyntactic processing within visually-presented compounds, as well as providing additional evidence that broader, N400-like negativities may also reflect constituent access or sensitivity to compound lexicality. More broadly, this study provides neurophysiological evidence for morpheme-based processing in compounds presented in the visual modality. The remaining studies discussed below examine morphological effects in visually-presented compounds which do not carry overt morphological cues (like infixes) to their internal structure, and test for effects of morphological decomposition and composition using comparisons between compound words and words without compound structure.

One EEG study which provides a direct comparison of visually-presented compounds and non-compounds, both lexicalized and novel, is El Yagoubi et al. (2008). El Yagoubi et al. (2008) examined the processing of Italian compounds in a visual lexical decision task. Their comparisons included left and right-headed compounds, noncompounds with initial-position pseudomorphemes, and noncompounds with final-position pseudomorphemes. Nonword conditions were generated by reversing the order of constituents in the above conditions. Their ERP results yielded a larger negativity in anterior regions for novel than for

lexicalized stimuli in a 270–370 ms time window, as well as an increased negativity for compounds than noncompounds in this time window. Headedness effects emerged in a slightly later, 310–360 ms window, while a larger lexicality effect for noncompounds than for compounds emerged in a 360–500 ms window. Lexicality effects and differences between compounds and non-compounds persisted into later time windows, in which headedness effects also remained evident. These results suggest that effects of compound structure can be elicited for both lexicalized and novel Italian compounds, on a similar time course (concomitant with the first emergence of lexicality effects). The authors also associate the negativity reflecting compound structure with the LAN component, as it had an anterior distribution, implicating (like Krott et al., 2006 and Koester et al., 2004) LAN effects in compound processing. El Yagoubi et al. (2008) hypothesize that their LAN effect may reflect the formation of complex representations for compound words. Moreover, the El Yagoubi et al. (2008) study illustrates that morphological effects may be elicited by visually-presented compounds that do not carry a morphological cue to their structure (cf., Krott et al., 2006).

English compounds, like Italian compounds, do not carry a regular morphological reflex of compound structure. Fiorentino and Poeppel (2007) provide evidence that lexicalized English compounds are decomposed into morphological constituents. They utilized a visual lexical decision task together with the electrophysiological brain-imaging method magnetoencephalography (MEG), comparing the processing of lexicalized compounds (e.g., *teacup*) and matched long monomorphemic words (e.g., *throttle*). The results showed faster response times and earlier latency of the M350 component, argued to index lexical access, for the compounds compared to the monomorphemic words. This finding was interpreted as reflecting constituent activation for the lexicalized compounds. As this study did not manipulate factors which may reflect post-decompositional, integrative processing, further neurophysiological research on the processing of English compounds is called for.[1] Moreover, effects of morphological constituent access and effects of morphological combination have rarely been investigated systematically within the same study (and have not been investigated with visually-presented lexicalized and novel English compounds, to our knowledge).

A recent study that approached this issue for auditorily-presented English compounds is MacGregor and Shtyrov (2013), who utilized a mismatch negativity paradigm and showed effects of whole-word frequency for semantically opaque but not transparent compounds in the mismatch negativity time window (130–160 ms post-onset of the second constituent), and increased negativities for transparent than opaque compounds, for low- compared to high-frequency compounds, and for pseudocompounds (akin to the novel compounds in the current study) in their N400 time window (350–400 ms post-onset of the second constituent). They interpret these effects as reflecting at least in part recourse to combinatorial processing for transparent compounds, with a more primary reliance on stored lexical representation for opaque compounds (since opaque compounds yielded effects of

[1]See also Pratarelli (1995) for a study on English auditorily presented compounds using a picture-word priming task, showing N400 responses sensitive to semantic relatedness among the picture and a subsequently presented compound with either full overlap or overlap of a shared morpheme among the picture and compound word.

frequency in the mismatch negativity, and less negative N400s than transparent compounds, which is taken to implicate less combinatorial processing).

As discussed above, investigating this issue with visually-presented compounds provides an important test case for the extent of morpheme-based processing in compounds, and for elucidating the neurophysiological mechanisms that support this processing. In the visual modality, compound appears at once rather than unfolding over time, and does not carry prosodic markers of morphological status like auditory compounds may (see, e.g., Koester et al., 2004; Isel, Gunter, & Friederici, 2003 for discussion of prosody in compounds); moreover, in English, compounds do not carry a morphological marker of compound structure, providing an important test case for the extent and nature of morphological processing in compound recognition in the absence of prosodic or morphological cues to internal structure. Thus, we turn to the investigation of morpheme access and combination in English visually-presented compounds in the current study.

Present Study

In the current study, we investigate the processing of English compounds during visual word recognition, probing for behavioral and neurophysiological effects of constituency and combinatorics in compound processing. Specifically, we examine the processing of lexicalized compounds, monomorphemic words which are matched on whole word properties to the lexicalized compounds, novel compounds, and unstructured nonwords which are matched to the novel compounds. The lexicalized and novel compounds are also matched on both whole-word and morpheme-level lexical variables. This allows us to probe for effects of morphological constituency, which should yield differences among compounds and non-compounds, both within the lexicalized conditions and within the novel conditions. This design also allows us to test whether effects of morphological structure emerge that are unique to the lexicalized conditions or to the novel conditions, and whether effects of structure emerge on similar or different time courses for the two compound types. Such effects unique to a particular compound type may implicate post-decompositional processes that the lexicalized and novel compounds may differentially engender (e.g., recognizing an attested morpheme combination, retrieving a meaning associated with a morpheme combination, or composing a meaning for the compound). These comparisons provide new tests of whether and under what circumstances a morpheme-based analysis is pursued for visually-presented lexicalized and novel putatively complex words with no morphological marker or other formally regular reflex of internal morphological structure, and provide a probe for the neurophysiological mechanisms subserving decomposition and composition in complex word recognition.

METHODS

Participants

Twenty-three monolingual native speakers of English participated in this experiment (16 female; mean age 20.0, range 18–23). All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), and had normal or corrected-to-normal

vision. All participants provided their written informed consent to participate in the study, and were paid $10/hour for their participation.

Stimuli

The experimental stimuli include 95 lexicalized compound words (e.g., *eggplant*), 95 long monomorphemic words (e.g., *throttle*), 95 novel complex words (e.g., *tombnote*), and 95 long non-morphemic nonwords (e.g., *blenyerp*), yielding a total of 380 stimuli. All four conditions were matched on letter length ($F < 1$, $p < 0.493$), and orthographic neighborhood, defined as the number of words of the same length as a given word, differing from the word string by one letter, ($F(3,376) = 1.669$, $p < 0.174$), calculated using the MCWord Database (Medler & Binder, 2005). The lexicalized compounds and long monomorphemic words were further matched on whole-word log frequency of occurrence ($t(188) = 1.321$, $p < 0.189$), using the Cobuild corpus (Collins Cobuild; http://www.cobuild.collins.co.uk). The lexicalized compound and novel compound conditions were also matched on first-morpheme log frequency ($t(188)=1.071$, $p < 0.286$), length ($t < 1$, $p < 0.732$), and orthographic neighborhood ($t < 1$, $p < 0.333$), as well as second-morpheme log frequency ($t(188)=1.613$, $p < 0.109$), length ($t < 1$, $p < 0.464$), and orthographic neighborhood ($t(188)=1.299$, $p < 0.189$). Mean values for each of these stimulus properties are provided in Table 1.[2]

We also conducted a pencil-and-paper pretest to acquire interpretability ratings for the lexicalized and novel compounds. Twenty-one monolingual native English speaking participants received extra credit for completing this rating task; no participant was also in the EEG study. Participants were instructed to rate how interpretable each compound was, on a 5-point scale (1 = very difficult to interpret, 5 = very easy to interpret). The overall mean rating for the lexicalized and novel compounds together was 3.45 (*range across stimuli* 1.42–5.00; *SE* = 0.08). The lexicalized compounds were overall rated more interpretable (*M* = 4.36, *range across stimuli* 3.08 to 5.00; *SE* = 0.05) than the novel compounds (*M* = 2.54, *range across stimuli* 1.42 to 4.42; *SE* = 0.05), $t(94) = 21.448$, $p < 0.001$. We will return to interpretability and its potential effects on response times and EEG responses in the Discussion.

Procedure

Participants completed the experimental task while seated in front of a computer monitor in a dimly-lit and sound-attenuated EEG testing room. Stimuli were presented in the center of

[2]Care was also taken to keep bigram frequency as similar as possible across conditions. No significant differences emerge at the morpheme-level between the lexicalized and novel compounds, either for the first or for the second morpheme. At the whole-word level, we were able to achieve similar bigram frequencies for all conditions save the long monomorphemic words (with the long monomorphemic words higher in bigram frequency than the other three conditions). While this potentially complicates the direct comparison of the long monomorphemic words and the lexicalized compounds, it is worth noting that, although there remain few studies on ERP responses related to phonological/orthographic probability/familiarity, we may predict that high probability should yield larger N400-like responses than lower probability (e.g., Rossi, Jürgenson, Hanulíková, Telkemeyer, Wartenburger, & Obrig, 2011; Friedrich & Friederici, 2005). Thus, results showing a higher-amplitude response for the long monomorphemic words would be consistent with a probability effect, although higher-amplitude responses for the compounds would suggest a contravening (structural) factor distinguishing the conditions; we report the latter finding in the current study. Moreover, we note that probability was controlled within the novel compound vs. novel non-word comparison, and within the lexicalized vs. novel compound comparison; thus, these comparisons provide probes for effects of morphological constituency, and for post-decompositional processing, respectively, which are not complicated by bigram differences.

the screen in Courier New text on a black background using *Paradigm* (Tagliaferri, 2005). The trial structure included the presentation of a fixation point (+) for 750 ms, followed by the presentation of the stimulus, which remained on the screen until the participant's button-press response or a 3000 ms timeout. Participants were instructed to respond as quickly and accurately as possible whether the stimulus presented was a word of English or not. "Word" responses were made by button press with the index finger of the participant's dominant hand, and nonword responses were made by button press with the middle finger of the participant's dominant hand. The stimuli were presented in a different randomized order for each participant. The main experiment was preceded by 8 practice trials, and 4 self-paced rest periods were provided (rest periods occurred at 76-trial intervals); the experiment was typically completed in approximately 45 minutes.

EEG Recording

EEG was recorded from 32 sintered, Ag/AgCl electrodes in an electrode cap (Electro-cap International, Inc.), arranged in a modified 10–20 layout (midline: FPz, Fz, FCz, Cz, CPz, Pz, Oz; lateral: FP1/2, F7/8, F3/4, FT7/8, FC3/4, T3/4, C3/4, TP7/8, CP3/4, T5/6, P3/4, O1/2), using a Neuroscan Synamps2 amplifier system (Compumedics Neuroscan, Inc.). Additional bipolar electrode pairs were placed above and below each eye (VEOL and VEOR, respectively), and on the left and right outer canthi of each eye (HEO). Impedances were kept below 5 kOhms. Data was continuously recorded in AC mode with an online high-pass filter of 0.1 Hz and low-pass of 200 Hz. Data were sampled at 1 kHz, and referenced to the left mastoid, and re-referenced offline to linked mastoids.

Data Analysis

Continuous EEG files were first visually screened for blinks, eye movements, and other large artifacts; the data from four participants were excluded due to excessive artifacts. The remaining data were carried forward for further processing. Trials were epoched by condition (−300 ms to 900 ms), baseline-corrected with respect to the 300 ms prestimulus interval, and averaged by condition. We defined six regions of interest (ROI) to be utilized in ANOVA analysis of the EEG data. The six regions included left anterior (F3, FT7, FC3), midline anterior (FZ, FCZ, CZ), and right anterior (F4, FT8, FC4), left posterior (TP7, CP3, P3), midline posterior (CPZ, PZ, OZ), and right posterior (TP8, CP4, P4). Four time windows of interest were identified for analysis following visual inspection of the data and in light of previous studies utilizing similar time windows (e.g., El Yagoubi et al., 2008): 0–275 ms post-onset, 275–400 ms post-onset, 400–700 ms post-onset, and 800–900 ms post-onset.[3] During the 0–275 ms time window, visual inspection suggests that the waveforms for all four conditions overlap. During the 275–400 ms time window the conditions appear to first diverge, with waveforms generally appearing more negative-going for conditions with compound structure and for novel conditions; this appears more pronounced for lexicalized than novel compounds during this time window. The waveforms all appear to be trending in a more negative-going direction than in the preceding time window. The conditions appear to diverge also in the 400–700 ms time window, with waveforms generally appearing more negative-going for conditions with compound structure and for

[3]We thank an anonymous reviewer for recommending that we analyze this part of the component.

novel conditions, with a greater apparent effect for the novel compounds than lexicalized compounds; the waveforms for all four conditions trend in a positive direction compared to the previous time window. In the 800–900 ms time window, there is a reversal of the effects for lexicalized compounds and monomorphemic words compared to how these two conditions patterned in the two previous time windows (this reversal is most clearly apparent in anterior regions). As we mention in the discussion, and as noted by an anonymous reviewer, the waveforms in this time window are the most reminiscent of the behavioral response time pattern we report below. Mean amplitudes in these time windows were entered into statistical analyses; all analyses were conducted on data that were not filtered offline.

Predictions

If both lexicalized and novel compounds are decomposed during visual word recognition, we predict effects of morphological constituency for both types of compound, compared to their unstructured counterparts. If lexicalized and novel compounds are processed on par, and if a brain-level reflex of decomposition can be elicited in EEG, we expect to see a brain-level effect of compound structure that is shared between lexicalized and novel compounds. If aspects of post-decompositional compound processing, such as recognizing the familiarity of the morpheme combination (for lexicalized compounds), forming a new morpho-syntactic representation (for novel compounds), and retrieving (possibly for lexicalized compounds) or composing a semantic representation (either solely for the novel compounds, or for both lexicalized and novel compounds, e.g., Gagné & Spalding, 2009), and if brain-level reflexes of these processes can be elicited in EEG, we expect to see some effects which are related to structure (i.e., differ between compounds and non-compounds) but are unique to one compound type, or that differ in size for the two compound types.

Regarding possible brain responses linked to the above-mentioned decompositional and combinatoric processes, we expect decomposition (activation of morpheme constituents) may be reflected by an N400-like negativity (e.g., McKinnon et al., 2003). Moreover, since N400 has been argued to reflect aspects of combinatorial processing (German: Holle et al., 2010; Koester et al., 2007, Koester et al., 2009; Chinese: Bai et al., 2008; see also Vergara-Martínez, Duñabeitia, Laka, & Carreiras, 2009, for attribution of N400 to selectional/integrational processing in Basque visually-presented compounds), it is possible that some aspects of the combinatoric processing of lexicalized and novel English compounds may also engender increased negativities in the N400 (or, as described in some of the literature, an N400-like negativity). However, it is also possible that some aspects of the combinatoric processing of lexicalized and/or novel compounds may engender anterior negativities (i.e., LAN effects; note that responses attributed in the literature to LAN often extend beyond the Left Anterior region into other anterior regions, and even extend sometimes to posterior regions). Such a response may reflect either morphosyntactic processing itself or morphosyntactic representation formation (e.g., El Yagoubi et al., 2008; Krott et al., 2006), or the working memory costs associated with these processes (e.g., Vos et al., 2001; see El Yagoubi et al., 2008 for discussion of this possibility).

In the behavioral lexical decision task, if the results of Fiorentino and Poeppel (2007), showing faster response times for compounds than long monomorphemic words hold in an experimental environment with large numbers of novel compounds, we expect to replicate this finding in the current study (see also Ji et al., 2011 and Fiorentino & Fund-Reznicek, 2008 for converging lexical decision evidence; cf. El Yagoubi et al., 2008, who report longer reaction times for compounds than long monomorphemic words). In contrast to the lexicalized compounds, we may expect the novel compounds to engender longer response times than unstructured nonwords; this pattern of results for lexicalized and novel compounds was indeed reported in a psycholinguistic study with a very similar design and stimulus set to the current study (Fiorentino & Fund-Reznicek, 2008). However, if the compounds are processed non-decompositionally in the current study, lexicalized and novel words should differ, but the presence or absence of putative compound structure should not affect lexical decision responses.

RESULTS

Behavioral Results

Mean response times for each condition are shown in Figure 1. As the pattern of results in Figure 1 suggests, effects of compound structure are evident in response time differences both for the lexicalized compound versus monomorphemic word comparison, and for the novel compounds versus non-morphemic nonword comparison, with faster response times for lexicalized compounds than monomorphemic words, and slower response times for novel compounds than non-morphemic nonwords. This pattern of results, replicating Fiorentino & Fund-Reznicek (2008) and extending the lexical decision findings of Fiorentino & Poeppel (2007) and Ji et al. (2011) to include the direct comparison of lexicalized and novel compounds, was confirmed in the statistical analysis reported below.

We analyzed response times across condition in a 2 (Structure: compound vs. non-compound) X 2 (Lexicality: lexicalized vs. novel) Repeated-Measures Analysis of Variance (ANOVA). The main effect of *Structure* was not significant by participants or items ($F_1 < 1$, $p > 0.475$; $F_2(1, 94) = 1.319$, $MSE = 6944.326$, $p < 0.255$). The effect of *Lexicality* was significant by participants and items $F_1(1, 18) = 24.957$, $MSE = 12684.375$, $p < 0.001$; $F_2(1, 94) = 104.991$, $MSE = 15075.843$, $p < 0.001$). Crucially, the *Structure* x *Lexicality* interaction was significant by participants and items ($F_1(1, 18) = 56.469$, $MSE = 2287.486$, $p < 0.001$; $F_2(1, 94) = 37.666$, $MSE = 16547.294$, $p < 0.001$).

Analysis of the simple effects of Lexicality by participants revealed a significant effect within the compound conditions, with the lexicalized compounds responded to faster than the novel compounds, $p < 0.001$; the effect for the non-compounds was only numerical by participants, $p < 0.103$. By items, there were significant effects of lexicality both within compounds ($p < 0.001$) and non-compounds ($p < 0.019$), with the lexicalized conditions responded to faster than the novel conditions. Effects of Structure were significant, but in opposite directions, for the lexicalized and the novel conditions, both by participants and by items. Lexicalized compounds were responded to faster than monomorphemic words (by participants: $p < 0.003$, by items: $p < 0.001$); novel compounds were responded to more slowly than unstructured nonwords (by participants: $p < 0.001$, by items: $p < 0.003$)

EEG Results

Within each time window of interest (0–275 ms, 275–400 ms, and 400–700 ms), mean amplitudes were analyzed using a 2 (Structure: compound, non-compound) X 2 (Lexicality: lexicalized, novel) Repeated-Measures ANOVA for each region of interest. Simple effects are reported in order to interpret any interactions between Structure and Lexicality. Grand averaged waveforms for each condition are shown in Figure 2.

Time Window 0–275 ms Post-onset

Neither Structure nor Lexicality yielded significant effects in this time window. The interaction among Structure and Lexicality was also non-significant. See Table 2 for a detailed summary of ANOVA results for each factor and region.

Time Window 275–400 ms Post-onset

A very broadly distributed effect of Lexicality emerged in this time window, reaching significance across regions, reflecting more negative-going waveforms for novel compared to lexicalized stimuli. A significant effect of Structure emerged in both Left Posterior and Midline Posterior regions. Structure did not interact with Lexicality in Left Posterior, but did interact marginally with Lexicality in Midline Posterior. Analysis of simple effects for each factor revealed that the interaction in Midline Posterior is driven by the presence of an effect of Structure only for the lexicalized conditions; that is, the lexicalized compounds were more negative-going than the monomorphemic words ($p < 0.014$), while no such effect emerged for the novel conditions ($p < 0.828$). The effect of Lexicality was significant for both levels of Structure in Midline Posterior (compound conditions: $p < 0.026$, non-compound conditions: $p < 0.001$). Lexicality and Structure marginally interacted in Right Posterior; once again, the effect of Structure was limited to the lexicalized conditions ($p < 0.044$) and was absent for the novel conditions ($p < 0.84$). The effect of Lexicality was marginal in Right Posterior for the compound conditions ($p < 0.075$), and significant for the non-compound conditions ($p < 0.001$).

To briefly summarize the pattern of effects in the 275–400 ms with respect to the role of morphological structure, an effect of structure that was common to the lexicalized and the novel conditions emerged in Left Posterior. Effects of Structure that were unique to the lexicalized conditions emerged in Midline Posterior and Right Posterior.

Table 3 presents a report of the *F* and *p* values for the main effects and interactions from the ANOVA for the 275–400 ms time window. Figure 3 provides topographic plots for this time window, illustrating the differences between the lexicalized compounds and monomorphemic words (leftmost plot), the novel compounds and nonwords (center plot), and the lexicalized and novel compounds (rightmost plot).

Time Window 400–700 ms Post-onset

In the 400–700 ms time window, a broad Lexicality was evident and significant across all regions, with novel conditions more negative-going than lexicalized conditions. The effect of Structure was also broadly distributed, with compound conditions more negative-going than non-compound conditions; the effect of Structure was significant in Left and Midline

Anterior regions, marginal in Right Anterior, and significant across the Left, Midline, and Right Posterior Regions. Structure and Lexicality interacted in all three anterior regions and in the Left Posterior region. Analysis of the simple effects for each factor revealed that the effect of Structure is limited to novel conditions in each of these regions (novel conditions: all $p < 0.009$), and is absent for the lexicalized conditions: all $p > 0.347$). The effect of Lexicality was significant in Left Anterior for the compounds ($p < 0.001$) and marginal for the non-compounds ($p < 0.077$), and was significant for both compounds and non-compounds Midline Anterior, Right Anterior, and Left Posterior (all $p < 0.026$).

In summary, effects implicating the role of morphological structure in the 400–700 ms time window were as follows: the effect of Structure was common to lexicalized and novel conditions in Midline Posterior and Right Posterior. Effects of Structure that were unique to novel compounds emerged in this time window in all three anterior regions, and in the Left Posterior region.

Table 4 provides a report of the *F* and *p* values for the main effects and interactions from the ANOVA for the 400–700 ms time window. Figure 4 provides topographic plots depicting the differences between the lexicalized compounds and monomorphemic words (leftmost plot), the novel compounds and nonwords (center plot), and the lexicalized and novel compounds (rightmost plot), for this time window.

Time Window 800–900 ms Post-onset

The effect of Lexicality was remained significant or marginal across all regions except Left Posterior, with novel conditions more negative-going than lexicalized conditions. The effect of Structure was marginal in Right Posterior, but was not significant or marginal in any other region. Lexicality and Structure interacted marginally in Right Anterior. Analysis of the simple effects for each factor revealed that the effect of Lexicality in this region was limited to compounds, with novel compounds more negative-going than lexicalized compounds, ($p < 0.023$), and is absent for the non-compounds: all $p < 0.627$). There were no simple effects of Structure for lexicalized or novel conditions in this region (all $p > 0.204$)

To summarize effects related to the role of morphological structure in the 800–900 ms time window: the marginal effect of Structure was common to lexicalized and novel conditions in Right Posterior (an effect which was also common to the lexicalized and novel conditions in the previous time window; it was significant in that window). An effect of Lexicality that was unique to compounds emerged in this time window Right Anterior.

Table 5 provides a report of the *F* and *p* values for the main effects and interactions from the ANOVA for the 800–900 ms time window. Figure 5 provides topographic plots depicting the differences between the lexicalized compounds and monomorphemic words (leftmost plot), the novel compounds and nonwords (center plot), and the lexicalized and novel compounds (rightmost plot), for this time window.

DISCUSSION

The current study examined the processing of visually-presented English lexicalized and novel compounds, using both response time and electrophysiological measures. The response time results revealed significant effects of constituency, showing that lexicalized compounds were responded to more quickly than their monomorphemic word counterparts, while novel compounds were responded to significantly more slowly than their unstructured nonword counterparts. The behavioral results for the lexicalized compounds replicate those of Fiorentino and Poeppel (2007), which examined the processing of lexicalized compounds and showed faster response times for lexicalized compounds than matched monomorphemic words. These findings also replicate those of the behavioral lexical decision study by Fiorentino and Fund-Reznicek (2008), which also showed faster response times for lexicalized compounds than matched monomorphemic words, and slower response times for novel compounds than unstructured nonwords (see also Ji et al., 2011, for faster RT for compounds than monomorphemic words when the stimulus set included novel compound fillers).

Effects in the 275–400 ms time window: Compound structure effects spanning lexicality, and effects unique to lexicalized compounds

The neurophysiological results revealed emerging sensitivity to lexicality and compound structure in the 275–400 ms time window (like the El Yagoubi et al., 2008 study on Italian compounds, neither Lexicality nor Structure affected responses in the 0–275 ms time window). Effects of Lexicality emerged in this time window, with novel words yielded more negative-going responses compared to lexicalized words broadly. These findings are consistent with the report of larger negativities for novel words and compounds in El Yagoubi et al. (2008) in similar time windows (e.g., their 270–370 ms window). In the El Yagoubi et al. (2008) study on Italian, the size of the word-nonword difference appears to be larger for the non-compound conditions. Broadly similar to El Yagoubi et al. (2008), in one of the two posterior regions in which there was a Lexicality by Structure interaction in 275–400 ms time window in the current study (Right Posterior), the effect of Lexicality was significant for the non-compounds, whereas it was only marginal for the compounds. Consistent with this pattern (and with El Yagoubi et al., 2008), the mean difference between the lexicalized and novel conditions for the non-compounds was larger than the mean difference for the lexicalized and novel compounds.

More central to our research questions regarding the role of morphological structure in lexicalized and novel compound processing, effects of Structure also emerged in the 275–400 ms time window, manifested by increased negativities for compounds compared to non-compounds (see also El Yagoubi et al., 2008 for increased negativities for compounds than non-compounds in this time range, although the responses were more anterior in that study; however, see also Lavric, Elchlepp, & Rastle, 2012 for a centro-parietal effect, more similar to in distribution to our posterior effects, distinguishing affixed words from pseudoaffixed words, emerging at approximately 250 ms post-onset). More specifically, an effect of Structure reflecting increased negativities for compounds than non-compounds emerged in this time window in Left Posterior, suggesting sensitivity to morphological structure for both

lexicalized and novel compounds in this time window. Interestingly, an effect of Structure unique to lexicalized compounds emerged in the Midline and Right Posterior regions, suggesting that to some extent, the processing of lexicalized and novel compounds can be distinguished even in this early time window.

Effects in the 400–700 ms time window: Compound structure effects spanning lexicality, and effects unique to novel compounds

Broadly-distributed effects of Lexicality remained through the 400–700 ms time window. While in El Yagoubi et al. (2008) it appears that the Lexicality difference remained greater for non-compounds than compounds in a similar (500–800 ms) time window on at least some electrodes, effects of Lexicality were generally numerically greater within the compounds than the non-compounds in the 400–700 ms time window in the current study, although effects of Lexicality were always present for both compounds and non-compounds alike save for Left Posterior, where the effect for non-compounds was marginal. Differences between the current study and El Yagoubi et al. (2008) include the language tested; it is often argued that noun-noun compounding is less productive in Italian than in English, for example (e.g., Marelli, Crepaldi, & Luzzatti, 2009). However, differences in the construction of the materials are also worth highlighting; in El Yagoubi et al. (2008), the novel compounds were constructed by reversing the morphemes in the lexicalized compounds, while in the current study, the novel compounds were not; moreover, the non-compounds in El Yagoubi et al. (2008) all contained embedded pseudomorphemes (with non-compound nonwords formed by reversing the position of the embedded pseudomorpheme in the word form to create a nonword). These properties may have yielded differences in how the compounds and/or the non-compounds were processed across the two studies, complicating to some extent direct comparisons across the two experiments. That said, the presence, direction, and time course of ERP effects related to morphological structure for lexicalized and novel compounds in the two studies provide fundamentally convergent evidence. In consideration of the remaining differences in the relative magnitude and topographical distribution of effects, the comparison of the two studies recommends further cross-linguistic ERP research on compound processing using designs that allow more direct comparisons, in order to inform our understanding of the nature of complex word processing across languages.

Crucially, effects of Structure (increased negativities for compounds compared to non-compounds) including those shared by lexicalized and novel compounds, and those unique to novel compounds, also emerged in this time window. Posterior effects of Structure that were common among the lexicalized and novel conditions were evident in Midline Posterior and Right Posterior regions (see also El Yagoubi et al., 2008 for more negative-going waveforms for compounds than non-compounds in their 500–800 ms time window). An effect of Structure unique to the novel compounds was evident across anterior regions, and in the Left Posterior region. We will return to the discussion of the presence of both shared and unique effects of Structure in these two time windows, and to discussion of the topographical distribution of effects, below.

Before discussing the potential functional implications of these effects, it is worth emphasizing out that the findings presented above are broadly consistent with the emergence of morphological effects for English lexicalized compounds in Fiorentino and Poeppel (2007) around 300–400 ms post word-onset using MEG. They are also broadly consistent with the emergence of increased negativities distinguishing Italian compounds and non-compounds in similar time windows in El Yagoubi et al. (2008), as discussed above. More broadly, these results converge with the set of auditory compounding studies examining languages like German (Holle et al., 2010; Koester et al., 2007; 2009) and Chinese (Bai et al., 2008), and with the study on visually-presented Basque compounds in sentences (Vergara-Martínez et al., 2009) in implicating negative-going electrophysiological responses in complex word processing.

Effects in the 800–900 ms time window: Comparison with earlier windows and behavioral responses

Examination of the ERP patterns in the 800–900 ms time window yielded some persisting effects of Lexicality and Structure. The only effect that was different between the lexicalized and novel compounds in this late time window was a Right Posterior effect of Lexicality that was unique to the compound conditions. It is also worth noting that the patterns of effects in this time window are, at least to some extent, isomorphic with the behavioral effects in ways that the previous time windows (275–400 ms and 400–700 ms) were not. For example, descriptively, this is the first time window in which the numerical pattern of ERP effects mirrors that of the behavioral response times; in the behavioral response times, the order of conditions from fastest to slowest RT was Lexicalized Compounds < Monomorphemic Words < Nonwords < Novel Compounds. Numerically, this pattern emerged with respect to ERP amplitudes for the first time in the 800–900 ms window; in order from least to most negative going, the mean amplitudes in both Left and Right Anterior are: Lexicalized Compounds < Monomorphemic Words < Nonwords < Novel Compounds. In the previous two time windows, compound conditions were numerically or significantly more negative-going than non-compounds within both the lexicalized and novel conditions. Moreover, the behavioral effect of Lexicality was significant only for the novel conditions in the by-participants analysis, an effect that mirrors the ERP effect of Lexicality in Right Anterior that was limited to novel conditions (although note that the behavioral effect did reach significance in the by-items analysis).

Behavioral Response Times: Significant, but opposite effects of constituency for lexicalized and novel compounds

Constituency effects were also evident in response times, where lexicalized compounds yielded faster response times, and novel compounds slower response times, than their unstructured counterparts. Thus, the brain-level effects of Structure, which took the form of increased negativities for both the lexicalized compounds and the novel compounds compared to their non-compound counterparts, dissociate in an interesting way from response times, where the consequence of morpheme access is faster recognition for known morpheme combinations on the one hand, and a concomitant slowdown for novel compounds on the other.

The role of morphological constituents in compound processing

The results of the current study provide new electrophysiological and behavioral evidence for morpheme-based processing of lexicalized and novel compound words, adding to the small number of neurophysiological studies examining the processing of compounds in the visual domain and extending this work to English. Addressing first the presence of effects of morphological structure within both the lexicalized and the novel compounds, our findings implicate morpheme-based processing for both lexicalized and novel compounds, consistent with across-the-board decomposition approaches (e.g., Stockall & Marantz, 2006; Taft, 2004). This evidence comes from compounds which do not carry prosodic cues (by virtue of testing visually-presented stimuli), regular orthographic clues like hyphens or spaces (by virtue of testing closed compounds), or morphological cues (like interfixes) indicating their morphological structure (by virtue of testing compounds in English). These findings run counter to approaches positing morpheme-based processing primarily or solely for novel words, and approaches which may predict morpheme effects solely for lexicalized words, as a consequence of learned associations among the putatively complex word and the representations of the constituents (e.g., Bybee, 1995).

Regarding the neurophysiological responses, the emergence of effects of Structure in the Left Posterior region in the 275–400 ms time window both for lexicalized and novel compounds suggests the operation of an initial decompositional process that is not modulated by lexicality; such an operation may be associated with initial decomposition into putative constituents (as has been argued in, e.g., Fiorentino & Poeppel, 2007). However, Midline and Right Posterior effects that were unique to lexicalized compounds also emerged in the 275–400 ms time window. Given that these effects were structure-related, but unique to the lexicalized compounds, it is possible that these effects are related to recognizing the familiar morpheme combination; making recourse to information about morpheme combinations is indeed consistent with full decomposition approaches like Taft (2004) and dual-route models like Schreuder and Baayen (1995). Alternatively, decomposing familiar compounds may facilitate access to stored semantic information, or facilitate rapidly initiating the online composition of the familiar compound’s meaning, which may be reflected in these Midline and Right Posterior negativities (see, e.g. Gagné & Spalding, 2009 for evidence suggesting that both lexicalized and novel compounds involve compositional processing, and that familiarity with a compound may aid in composition, rather than preclude it.)

The Midline and Right Posterior regions, showing a unique effect of Structure for the lexicalized conditions at 275–400 ms, later showed an effect of Structure regardless of Lexicality (400–700 ms) suggesting that these regions are not recruited solely for lexicalized compounds, raising the possibility that they underlie an aspect of morphological processing shared by lexicalized and novel compounds. Interestingly, effects of Structure unique to novel compounds emerged for the first time in the 400–700 ms time window; this effect was spread across the anterior regions, where effects of Structure for the lexicalized compounds never emerged; this effect was also present uniquely for the novel compounds in the Left Posterior region. Since the novel compounds lack any kind of pre-existing representation (either of the morpheme combination or a semantic representation), it is possible that this

unique, primarily anterior activation may index the formation of a new morphosyntactic and/or morpho-semantic representation (plausible representation construction operations include encoding the morpheme combination, constructing its morphological structure, and attempting to compose a meaning for the combination). As discussed by El Yagoubi et al. (2008), anterior negativities (i.e., LAN) have been related to morphosyntactic processing (e.g., Friederici, 1995), complex word processing specifically (see, e.g., Krott et al., 2006, and Koester et al., 2004) and more generally to working memory load incurred during the processing of complex structures, including the processing of morphosyntax (e.g., Vos et al., 2001, among others).

The current study demonstrates that both shared effects of structure (suggesting decomposition regardless of lexicality) and effects unique to each compound type (suggesting post-decompositional processes that may affect the two types differentially) can be elicited in English visually-presented lexicalized and novel compounds presented in the same experimental context, for the first time that we are aware of. Given these patterns, it becomes important to attempt to better understand their functional contributions. Some alternative possibilities are mentioned above; in part, it will simply be necessary to conduct further research attempting to systematically manipulate stimulus variables which may associate with different post-decompositional processes. One way in which we may begin to examine such associations is to take advantage of the fact that our compounds (both lexicalized and novel) vary to some extent in their ease of interpretability. The interpretability/transparency rating of a compound is one variable commonly used to probe compositional aspects of compound processing (Libben, 2006, Shoolman & Andrews, 2003, Fiorentino & Fund-Reznicek, 2009, among others). If interpretability ratings capture at least in part the ease of forming a semantic representation of the morpheme combination, they would serve as a useful probe of whether any of the brain responses identified above are modulated by semantic combinatorics.

As a first step in conducting this test, we determined whether response times for the lexicalized compounds, and for the novel compounds, were modulated by the interpretability of the morpheme combinations. To do so, we conducted correlation analyses for the by-items response time data for each compound type. Rated interpretability showed a significant negative correlation with response times for the lexicalized compounds ($r = -.308$, $p < 0.003$). Rated interpretability also showed a significant correlation with response times for the novel compounds, although the correlation was positive ($r = .419$, $p < 0.001$). This illustrates that the interpretability of the morpheme combination influenced responses for both the lexicalized and the novel compounds. For the lexicalized compounds, increased interpretability led to faster judgments; increased interpretability led to increased response times for the novel compounds (for converging evidence for RT delays for relatively high-interpretability novel compounds, see, e.g., Coolen, Van Jaarsveld, & Schreuder, 1991). This pattern of results suggests that responders are able to more rapidly accept a lexicalized compound when a meaning can be easily composed for it, while it is difficult to reject novel compounds (which are, after all, morphologically well-formed though not attested) as “not a word of English” when a meaning can be easily composed. Relevant for the current discussion, this behavioral pattern suggests the possibility that we might be able to

determine whether any of the brain-level responses elicited in the current study are modulated by interpretability, which would in turn allow us to propose that the response may be linked to morpho-semantic composition.

We then examined potential effects of interpretability on the EEG responses to the lexicalized compounds by comparing higher-interpretability (mean rating = 4.71, SE = .022) vs. lower-interpretability (mean rating = 4.04, SE = .046) subsets of the lexicalized compounds, while keeping the other lexical variables from the main analysis constant across the conditions. These subsets were comprised of 38 stimuli each. We also constructed higher-interpretability (mean rating = 3.013, SE = .0078) vs. lower-interpretability (mean rating = 1.97, SE = .039) subsets of the novel compounds, while keeping the item control variables from the main analysis constant. Interpretability did not significantly affect responses in the three time windows 0–275 ms, 275–400 ms, and 400–700 ms analyzed above. Further examination of EEG responses at 100 ms time intervals showed a marginal effect for the lexicalized compounds in the 200–300 ms time window in Left Posterior, $t(18) = 1.989$, $p < 0.063$), and a significant effect in the 400–500 ms time window in Right Anterior, $t(18) = 2.414$, $p < 0.028$), together with marginal effects in Right Posterior, $t(18) = 1.910$, $p < 0.073$) and Midline Anterior, $t(18) = 1.743$, $p < 0.099$), reflecting more negative-going waveforms for the high-interpretability than for the low interpretability lexicalized compounds (consistent with Koester et al., 2007 and MacGregor & Shtyrov, 2013, who note greater negativities for more semantically transparent stimuli). Among these effects, the Left Posterior effect at 200–300 ms and the Right Posterior effect at 400–500 ms fall at least in part within regions and time windows for which there was an effect of Structure that was either unique to lexicalized compounds (200–300 ms) or which held regardless of the lexicality of the compound (400–500 ms). For the novel compounds, interpretability effects were limited to a very early effect in the 0–100 ms time window in Midline Anterior, $t(18) = -1.776$, $p < 0.094$).

One speculation given the pattern described above would be that the lexicalized compounds, by virtue of their attested morpheme combination, have meanings composed (or activated, if such meanings are stored but still yield different levels of activation depending on ease of interpretability) rapidly in posterior regions (and potentially, anterior regions, according to the correlation results, although anterior regions did not yield effects of Structure overall for lexicalized compounds in the main ANOVA analysis). Given the lack of a similar effect for the novel compounds even in later time windows, one could argue that this interpretability effect may be reflecting relative ease of retrieving a stored meaning (or even the relative strength of the morpheme combination representation in the lexicon, if that may be modulated in turn by interpretability) would be a more plausible interpretation than relating the effect to semantic composition itself. However, one should be cautious in interpreting these results; since the subsets of compounds tested in the current study did not differ largely in rated interpretability, and the novel compounds were largely nonsensical, low-interpretability combinations, future research examining sets of compounds differing more in rated interpretability would be informative in determining how robust these patterns related to interpretability are.

Thus, the findings of the current study call for further investigation of the precise nature of the post-decompositional mechanisms involved in the processing of compounds, including to what extent lexicalized and novel compound processing engages semantic compositional mechanisms (see, e.g., Gagné & Spalding, 2009 for an approach to compound composition making recourse to relational structures; for an EEG study probing relation information in Chinese compounds using a relation priming paradigm, see Jia, Wang, Zhang, and Zhang, 2013). Indeed, the contribution of morpheme meaning to the processing of compounds has been recently raised as a challenge to both obligatory decomposition and dual-route models by Kuperman (2013), who argued that a range of semantic properties of morphemes did not affect recognition of compounds, as tested with lexical decision latencies. As pointed out by an anonymous reviewer, it is possible that brain-level data may provide an alternative way to probe the extent to which morpheme meanings contribute to the process of assigning meanings to compounds, given that there may be brain responses related to combinatorial processing that are not isomorphic to the eventual behavioral lexical decision patterns.

Moreover, additional studies are called for which utilize either passive reading tasks, or tasks in which the behavioral judgment is not directly related to Lexicality. As also noted by an anonymous reviewer, one fundamental challenge with including Lexicality in lexical decision designs like the current study is that Lexicality may then be confounded with participants' Answer. Thus, the presence/absence of an effect of Structure within a level of Lexicality might then be recast as an effect within a level of Answer. As we cannot easily disambiguate these two potential interpretations of the Lexicality factor in principle within a lexical decision task, task manipulations would provide a clear way forward in better understanding what underlies the Lexicality difference. One way to explore whether participants' answering behavior may be contributing to the EEG effects elicited in the current study is to correlate individuals' level of responding 'yes' to novel compounds (which goes against the coded 'no' Lexicality of those compounds) with the EEG effects involving novel compounds. While individuals are very accurate (i.e., their answers agree with coded Lexicality) for nonwords (mean 99%, standard deviation 2%), individuals do vary with respect to how likely they are to accept a novel compound (mean 85%, standard deviation 21%); this is perhaps unsurprising, as the novel compounds are morphologically well-formed, and some of them are relatively easy to generate an interpretation for. For the present purposes, this provides a context in which there is at least some difference between coded Lexicality and participant Answer.

We correlated the size of individuals' behavioral difference between novel compounds and nonwords in percent of 'no' answer (for these two conditions, a 'no' answer accords with coded Lexicality), and individuals' size of ERP effects for novel compounds vs. nonwords in each region and time window.[4] No significant correlations emerged in any region/time window for which an effect of Structure within novel conditions had emerged in the ANOVA analyses. The sole significant correlation emerged in the 275–400 ms time window, in Left Anterior. In this time window/region, the larger the ERP difference between

[4]We report the difference between a participant's accuracy with nonwords and their accuracy with novel compounds as the behavioral correlate here; however, we also verified that the same holds if the novel compound accuracy itself is used as the behavioral correlate, thus ensuring that the pattern is not due to variability within the nonwords rather than the novel compounds.

the novel compounds and the nonwords, the smaller the difference in Answer between the novel compounds and the nonwords ($r = -.457$, $p < 0.05$). That is, the larger the ERP difference, the less the novel compounds were answered 'yes' – i.e., the more they were rejected more on par with the nonwords). This exploratory test suggests that to the extent that individuals vary in answer for the novel compounds, that variation did not capture significant variation in the size of individuals' EEG effects.

In contrast, note that the difference in Answer did correlate with the size of the response time difference for the novel compound vs. nonword comparison; that is, the more an individual is rejecting novel compounds on par with nonwords, the greater the behavioral response time slowdown for the novel compounds compared the nonwords ($r = 0.718$, $p < 0.002$). The presence of this behavioral correlation in the absence of correlations with EEG effects of structure provides further evidence suggesting that the behavioral response is reflecting decision-stage processes subsequent to the processes reflected by the ERP structure effects.

The lack of effect of answering behavior on EEG effects does not, however, rule out the possibility that individual differences in answer modulate EEG effects; there could be effects of "answer" that were missed because of conducting correlations with a relatively low N, because the variability in answering behavior or in the EEG effects is not great enough, or because the relationship between answer and EEG effect size may be of a more complex nature than a linear correlation would capture, among other possibilities. The general lack of correlations between answering behavior and ERP effects is consistent with the claim that, in cases in which answer deviated from Lexicality for novel compounds, answering behavior did not capture significant variability in the size of EEG effects of structure; however, as stated above, manipulation of task in future studies would be a much more straightforward way to address this issue.

Summary

The current study provides new evidence suggesting across-the-board decomposition of putatively complex words into morpheme-level constituents, consistent with models positing full decomposition. Using visually-presented English compounds, we demonstrated that the processing of both lexicalized and novel compounds involves recourse to morphological structure. The neurophysiological results presented here yielded effects of morphological structure that were shared by lexicalized and novel compounds, as well as effects that were unique to each compound type. Moreover, the direction of the effects of structure (increased negativities for each compound type relative to their non-compound comparison condition) dissociates from that of the subsequent behavioral responses, for which the effects of compound structure went in opposite directions (leading to faster response times for lexicalized compounds but delayed response times for novel compounds, relative to their non-compound counterparts). These findings together support a neurocognitive model of lexical processing that includes a morpheme-based route, involving not only decomposition into morphological constituents but also combinatorial processes operating on those decomposed representations.

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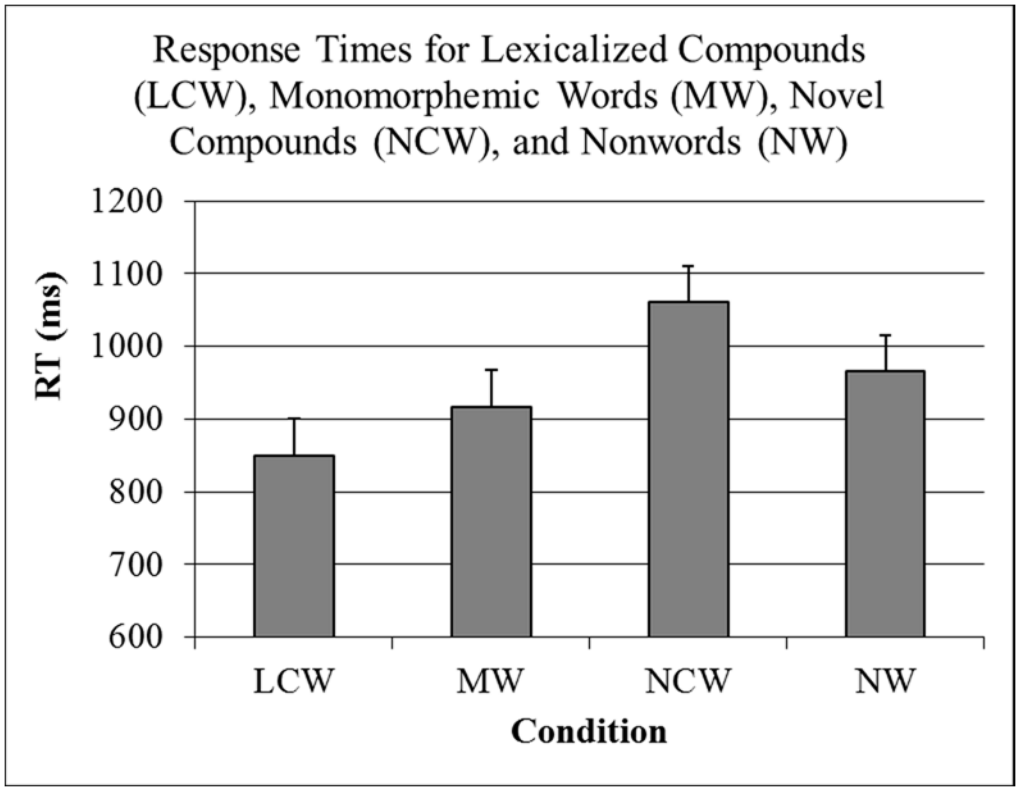

Figure 1. Response Times by Condition

Figure 1 presents the by-participants mean lexical decision response times for each of the four conditions: lexicalized compounds (LCW), monomorphemic words (MW), novel compounds (NCW), and nonwords (NW). The error bars depict standard error of the mean.

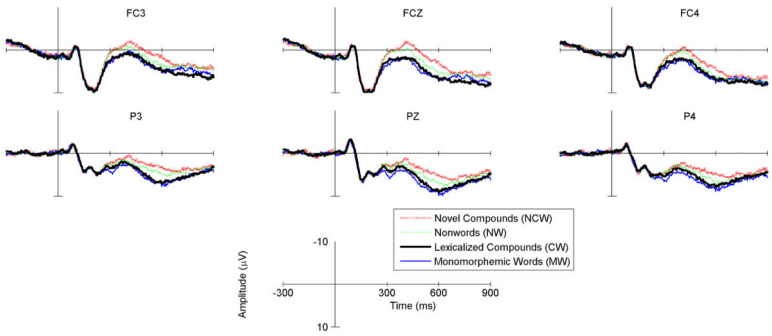

Figure 2. ERP Waveforms by Condition

Figure 2 illustrates mean waveforms for the novel compounds (thick, red, dashed lines); unstructured nonwords (thin, green, dashed lines); lexicalized compounds (thick, black smooth lines, and monomorphemic words (thin, blue, smooth lines). Waveforms are plotted for representative electrodes from each of the six regions of interest (Left, Midline and Right Anterior; Left, Midline, and Right Posterior).

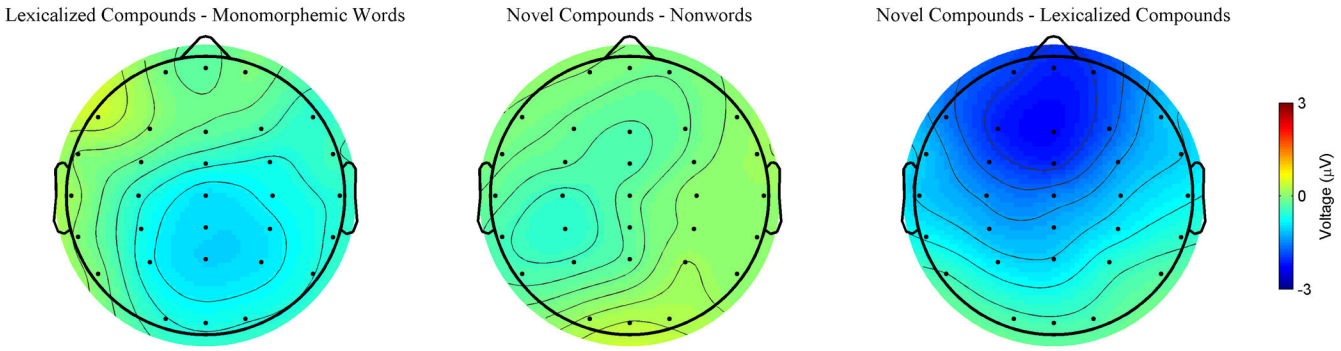

Figure 3. Topographic Plots, 275–400 ms Time Window

Figure 3 presents topographic plots illustrating the differences between lexicalized compound words and monomorphemic words (leftmost plot), novel compounds and nonwords (center plot), and lexicalized vs. novel compounds (rightmost plot). These comparisons are plotted for the 275–400 ms time window.

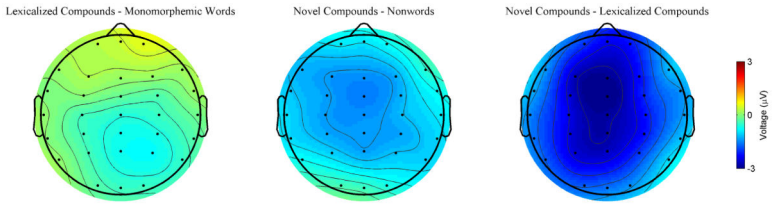

Figure 4. Topographic Plots, 400–700 ms Time Window

Figure 4 presents topographic plots illustrating the differences between lexicalized compound words and monomorphemic words (leftmost plot), novel compounds and nonwords (center plot), and lexicalized vs. novel compounds (rightmost plot). These comparisons are plotted for the 400–700 ms time window.

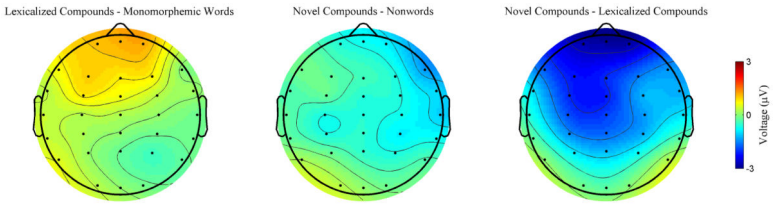

Figure 5. Topographic Plots, 800–900 ms Time Window

Figure 5 presents topographic plots illustrating the differences between lexicalized compound words and monomorphemic words (leftmost plot), novel compounds and nonwords (center plot), and lexicalized vs. novel compounds (rightmost plot). These comparisons are plotted for the 800–900 ms time window.

Table 1

Mean length (in letters), log frequency of occurrence (Cobuild corpus, Collins Cobuild; http://www.cobuild.collins.co.uk), and orthographic neighborhood (number of words of the same length as a given word, differing from the word string by one letter; Medler & Binder, 2005) values for each condition. Whole-word level properties are reported for all four conditions; morpheme-level properties are also reported for the lexicalized and novel compound conditions.

Condition	Length (SE)	Log Frequency (SE)	Orthographic Neighborhood (SE)
Monomorphemic Words	8.23 (.101)	0.27 (.068)	0.116 (.052)
Lexicalized Compounds	8.48 (.122)	0.16 (.053)	0.032 (.018)
Nonwords	8.36 (.118)	*a*	0.032 (.023)
Novel Compounds	8.36 (.118)	*a*	0.042 (.021)
Morpheme-Level Properties			
Lexicalized Compounds, First Morpheme	4.23 (.088)	1.73 (.057)	9.57 (.585)
Novel Compounds, First Morpheme	4.19 (.085)	1.82 (.064)	8.74 (.622)
Lexicalized Compounds, Second Morpheme	4.25 (.091)	1.71 (.062)	9.37 (.651)
Novel Compounds, Second Morpheme	4.17 (.07)	1.86 (.067)	10.53 (.608)

[a]Non-word stimuli

Table 2

ANOVA Results for Time Window 0–275 ms

Region	Structure	Lexicality	Structure x Lexicality
Left Anterior	$F(1,18)=0.904$, $p<0.354$	$F(1,18)=2.069$, $p<0.168$	$F(1,18)=0.967$, $p<0.338$
Midline Anterior	$F(1,18)=2.791$, $p<0.112$	$F(1,18)=1.706$, $p<0.208$	$F(1,18)=0.228$, $p<0.639$
Right Anterior	$F(1,18)=1.958$, $p<0.179$	$F(1,18)=1.043$, $p<0.321$	$F(1,18)=0.348$, $p<0.563$
Left Posterior	$F(1,18)=0.145$, $p<0.708$	$F(1,18)=0.615$, $p<0.443$	$F(1,18)=0.008$, $p<0.932$
Midline Posterior	$F(1,18)=0.700$, $p<0.414$	$F(1,18)=0.058$, $p<0.812$	$F(1,18)=1.835$, $p<0.192$
Right Posterior	$F(1,18)=1.690$, $p<0.210$	$F(1,18)=0.058$, $p<0.813$	$F(1,18)=0.506$, $p<0.486$

$^{\dagger}p < .1$;

$^{*}p < .05$;

$^{**}p < .01$.

Table 3

ANOVA Results for Time Window 275–400 ms

Region	Structure	Lexicality	Structure X Lexicality
Left Anterior	$F(1,18)=0.187$, $p<0.671$	$F(1,18)=27.296$, $p<0.001^{**}$	$F(1,18)=0.073$, $p<0.791$
Midline Anterior	$F(1,18)=2.437$, $p<0.136$	$F(1,18)=30.666$, $p<0.001^{**}$	$F(1,18)=0.217$, $p<0.647$
Right Anterior	$F(1,18)=0.771$, $p<0.392$	$F(1,18)=26.891$, $p<0.001^{**}$	$F(1,18)=0.634$, $p<0.436$
Left Posterior	$F(1,18)=4.539$, $p<0.047^{*}$	$F(1,18)=12.959$, $p<0.002^{**}$	$F(1,18)=0.016$, $p<0.900$
Midline Posterior	$F(1,18)=5.088$, $p<0.037^{*}$	$F(1,18)=18.693$, $p<0.001^{**}$	$F(1,18)=3.971$, $p<0.062^{\dagger}$
Right Posterior	$F(1,18)=2.404$, $p<0.138$	$F(1,18)=19.765$, $p<0.001^{**}$	$F(1,18)=3.312$, $p<0.085^{\dagger}$

$^{\dagger}p < .1$;

$^{*}p < .05$;

$^{**}p < .01$.

Table 4

ANOVA Results for Time Window 400–700 ms

Region	Structure	Lexicality	Structure X Lexicality
Left Anterior	$F(1,18)=4.838$, $p<0.041^{*}$	$F(1,18)=18.785$, $p<0.001^{**}$	$F(1,18)=7.612$, $p<0.013^{*}$
Midline Anterior	$F(1,18)=8.903$, $p<0.008^{**}$	$F(1,18)=46.809$, $p<0.001^{**}$	$F(1,18)=5.926$, $p<0.026^{*}$
Right Anterior	$F(1,18)=4.344$, $p<0.052^{\dagger}$	$F(1,18)=22.182$, $p<0.001^{**}$	$F(1,18)=6.15$, $p<0.023^{*}$
Left Posterior	$F(1,18)=10.627$, $p<0.004^{**}$	$F(1,18)=23.071$, $p<0.001^{**}$	$F(1,18)=6.822$, $p<0.018^{*}$
Midline Posterior	$F(1,18)=25.510$, $p<0.001^{**}$	$F(1,18)=33.377$, $p<0.001^{**}$	$F(1,18)=1.597$, $p<0.222$
Right Posterior	$F(1,18)=33.743$, $p<0.001^{**}$	$F(1,18)=31.397$, $p<0.001^{**}$	$F(1,18)=2.266$, $p<0.150$

$^{\dagger}p < .1$;

$^{*}p < .05$;

$^{**}p < .01$.

Table 5

ANOVA Results for Time Window 800–900 ms

Region	Structure	Lexicality	Structure X Lexicality
Left Anterior	$F(1,18)=0.362$, $p<0.556$	$F(1,18)=10.572$, $p<0.005^{**}$	$F(1,18)=1.144$, $p<0.3$
Midline Anterior	$F(1,18)=0.001$, $p<0.973$	$F(1,18)=11.146$, $p<0.005^{**}$	$F(1,18)=1.138$, $p<0.31$
Right Anterior	$F(1,18)=0.288$, $p<0.599$	$F(1,18)=4.129$, $p<0.058^{\dagger}$	$F(1,18)=3.552$, $p<0.077^{\dagger}$
Left Posterior	$F(1,18)=0.062$, $p<0.806$	$F(1,18)=1.557$, $p<0.229$	$F(1,18)=0.717$, $p<0.409$
Midline Posterior	$F(1,18)=0.466$, $p<0.504$	$F(1,18)=3.419$, $p<0.089^{\dagger}$	$F(1,18)=0.18$, $p<0.677$
Right Posterior	$F(1,18)=3.271$, $p<0.088^{\dagger}$	$F(1,18)=31.397$, $p<0.001^{**}$	$F(1,18)=0.769$, $p<0.393$

$^{\dagger}p < .1$;

$^{*}p < .05$;

$^{**}p < .01$.