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Compounding matters: Event-related potential evidence for early semantic access to compound words

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ABSTRACT

Reading words in a native language triggers a largely obligatory cognitive process that we accept as leading to comprehension of the word – we cannot suppress our understanding of word meaning. In this study, we investigated the early stages of this comprehension process by means of event-related potentials (ERPs) to identify when this processing of meaning – that is, semantic processing – first occurs. We report that, when processing visually presented compound words, semantic access at some level occurs as early as the P100 and persists through to the N400. Specifically, we focused on the P100 ERP component, and utilized the unique features of compound words (i.e. variation in the transparency of meaning) to investigate the speed with which we gain access to information about *meaning* (i.e. semantic access). Twenty-two participants performed a lexical decision task including 40 English compounds, which varied with respect to their constituent semantic transparency. Compounds ranged from full constituent semantic transparency (e.g. *grapeseed*) to partial transparency (e.g. *grapefruit*) to full opacity (e.g. *hogwash*). Regression analyses predicted ERP components from compound constituent transparency, adjusting for word frequency. Word frequency and transparency of both the first and second constituents each uniquely predicted P100 amplitude. Transparency of the second constituent, but not word frequency, predicted later component amplitudes, including that of the N400. The findings suggest that some level of semantic access occurs as early as the P100. Overall, these results support models which emphasize simultaneous processing of form and meaning as opposed to serial or hierarchical approaches.

1. Introduction

When reading words in a native language, it is impossible to suppress the understanding of those words. Thus, seeing the word *grapefruit* can be said to trigger a largely obligatory cognitive process that we accept as leading to comprehension of the word *grapefruit*. Our goal here is to probe the early components of this comprehension process and identify the stage(s) at which semantic processing first occurs, and moreover, the relative speed with which we gain access to information about *meaning* (i.e. semantic access) in complex words like *grapefruit*. To address these issues, we focused on event-related potentials (ERPs) associated with the processing of compound words.

1.1. Early processes in visual word reading

It is largely agreed that the process by which we come to recognize words involves a set of overlapping or cascaded processes (e.g. Barber & Kutas, 2007; Dien, 2009; Hauk, Coutout, Holden, & Chen, 2012), and models of word recognition suggest that these processes are interactive and mutually constraining (e.g. Grainger & Holcomb, 2009; Harm & Seidenberg, 2004). Accordingly, much work has focused on precisely when these cascaded processes operate and how they overlap and interact. Lexical-semantic factors affect ERP components within the first 200 ms after seeing a word, as early as the N200 (e.g. Dien, Frishkoff, Cerbone, & Tucker, 2003), the N170 (e.g. Hauk & Pulvermüller, 2004; Hauk, Pattersonauk, et al., 2006; Sereno, Rayner, & Posner, 1998), and even the P100 (Penolazzi, Hauk, & Pulvermüller, 2007; Segalowitz & Zheng, 2009) or M100 in magnetoencephalography (MEG; Pulvermüller, Assadollahi, & Elbert, 2001), although Segalowitz and Zheng (2009) and Pulvermüller et al. (2001) acknowledge serious limitations due to their study designs. More recently, it has been shown that conceptual-semantic properties such as imageability and animacy

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may affect ERP amplitudes as early as 100–200 ms post-stimulus (Amsel, 2011; Amsel, Urbach, & Kutas, 2013; Lewis & Poeppel, 2014). Yet other research suggests that visual cues providing information about the syntactic properties of words (e.g. the *-ed* suffix) are processed early by sensory cortices (i.e. occipital cortex for visual language), suggesting that in addition to semantic properties, syntactic form can influence early processing (Dikker, Rabagliati, & Pylkkanen, 2009; Dikker, Rabagliati, Farmer, & Pylkkanen, 2010). Indeed, while these studies suggest that several sources of information are available to readers early on, there remain gaps in our understanding of the degree to which different sources of information, particularly sources pertaining to different aspects of complex words, come online at particular times.

While work on simple word and sentence processing has revealed both form- and meaning-based characteristics of words to be active in the earliest stages of visual language processing, electrophysiological research investigating complex word processing – primarily focused on processing of derived words (e.g. dream*er*) – has largely endorsed a serial, *form-then-meaning* approach. In contrast to the aforementioned work on simple words and sentences, studies on complex word processing suggest that effects of visual form emerge in the first 100–250 ms after stimulus presentation, with semantic effects emerging later, typically in the window of 250–500 ms post-stimulus (e.g. Fruchter & Marantz, 2015; Solomyak & Marantz, 2010; for review, see Rastle & Davis, 2008; but see e.g., Feldman, O'Connor, & del Prado Martin, 2009; Feldman et al., 2015; Jared, Jouravlev, & Joanisse, 2017, for conflicting evidence). This body of work is at odds with a wealth of evidence suggesting that word meaning is accessed at least as early as word form – why should it be the case that meaning is accessed by 100–200 ms in some words, but not in others? Here, we suggest that compound words present an ideal opportunity for investigating the relative speed with which we gain access to meaning- and form-based information in complex visual word processing.

1.2. So, why compound words?

Compound words (e.g. *grapeseed* and *grapefruit*) offer a special opportunity to probe early semantic processing first because, like other complex words, they are multimorphemic – that is, they have more than one meaningful subcomponent. Among the world's languages, English has a relatively simple morphological system, in which monomorphemic words such as *grape* are relatively common. But even in a language like English, a great many words are multimorphemic, either because they are compounded (e.g. *grapeseed*) or because they are prefixed (e.g. *re-seed*) or suffixed (e.g. *seeder*). The presence of multimorphemic words in a language seems to offer several processing advantages. First, it enables novel words to be understood more easily. Thus, if a native speaker of English encounters a string such as *grapeseed oil* for the first time, it is relatively easily interpreted as '*oil made of the seeds of grapes*'. A comparison sentence word such as *grole oil*, in which *grapeseed* is replaced by a novel monomorphemic word, would be much more difficult to interpret.

The examples above raise several considerations that are important to the role that compound words can play in advancing our understanding of semantic processing. One important set of issues concerns the semantic aspects of compound words. The processing of compound words may be particularly revealing of early semantic processing, namely, because the functions of morphemes within a compound do not always correspond in a semantically transparent way to their meanings as whole words, and the morphemes that make up a compound do not 'give away' their complex structure based on form alone (like the suffix *-ed*, for example). Consider, as examples, the compounds *grapeseed* and *grapefruit*. The constituent *grape* contributes semantically in a straightforward way to the overall meaning of the compound *grapeseed,* unlike the contribution of *grape* to the meaning of the word *grapefruit*, which requires specialized knowledge that it is not a fruit made of grapes. Moreover, the element *grape* and the whole compound *grapefruit* may be in competition as different types of fruits. A compound such as *grapefruit* may be considered semantically opaque, or more specifically, an opaque-transparent compound (Libben, Gibson, Yoon, & Sandra, 2003), because the opacity is localized to the initial constituent of the compound.

The distinction between semantically transparent and opaque compounds has played a large role in psycholinguistic experimentation on compound processing and modelling of the representation of compound words in the mind and brain. One reason for this is that the distinction plays a role in how the semantic processing of compound words can be conceptualized. In early models (e.g. Taft & Forster, 1976), it was assumed that all compound words are accessed in terms of their constituents, so that the recognition of a compound such as *grapeseed* is achieved through prior recognition of its constituents, *grape* and *seed*. Semantically opaque compounds present problematic cases for such a view. Clearly, the comprehension of a compound such as *grapefruit* cannot depend on the comprehension of *grape* and *fruit*. In fact, it would seem that the interpretation of the meaning of the whole word depends on full or partial suppression of constituent meaning. Seminal work by Sandra (1990) investigated this through a semantic priming paradigm in which it was found that a word such as *death* will facilitate recognition (shorter lexical decision latencies) of a transparent compound such as *birthday*. However, Sandra (1990) also found that a word such as *moon* will not facilitate recognition of a compound such as *Sunday*, in which the first constituent is semantically opaque (see also Zwitserlood, 1994). In addition, Gagné and Spalding (2009) and Ji, Gagné, and Spalding (2011) investigated the contributions of semantic transparency and patterns of semantic relations to the processing of compound words. They found that initial decomposition facilitates (i.e. speeds up) processing of transparent compounds, but slows down processing of opaque compounds, presumably because of the conflict between constituent meaning and whole word meaning.

These findings have engendered a consensus in the literature that, at least at a behavioural level, semantic transparency has a facilitative effect on complex word processing. That is, when the semantic relation between constituents is strong, as is the case in transparent compounds like *grapeseed*, a processing boost is observed (e.g. Libben et al., 2003). While the results of time-course investigations have been more mixed, several eye-tracking studies also support the facilitative effect of semantic transparency. For example, transparent compounds in English show shorter gaze durations in sentential contexts (e.g. Underwood, Petley, & Clews, 1990), though this effect seems inconsistent (e.g. Frisson, Niswander-Klement, & Pollatsek, 2008, Exp. 1) and may be dependent on whether decomposition is encouraged or not (e.g. when compounds are presented in spaced format, the effect emerges; Frisson et al., 2008, Exp. 2). In spite of these discrepant findings, there is generally agreement that compound transparency facilitates processing of compound words, but that the effect may be modulated by factors such as individual differences and how transparency is operationalized (for discussion, see Schmidtke, Van Dyke, & Kuperman, 2017). Using ERPs, with a focus on early components, might afford us greater sensitivity to pre-response cognitive processing, thus offering a window into the early influence of transparency on compound processing.

As the above discussion indicates, the processing of compound words can involve word-internal semantic activation as well as the need to deal with semantic mismatches and the establishment of cognitive relations among roots. This word-internal semantic complexity has placed compound processing at the centre of discussions concerning how the semantics of the whole word and its constituents are handled in lexical processing in general. The early literature contrasted claims of full listing of all multimorphemic words (e.g. Butterworth, 1983) to full decomposition models (e.g. Taft & Forster, 1976). The dual-route model of Baayen, Dijkstra, and Schreuder (1997) provides a means of conceptualizing the processing of multimorphemic words as a race between whole-word access and morphological decomposition routes. More recently, Kuperman, Schreuder, Bertram, and Baayen (2009) presented a multiple-route model that postulates early, simultaneous access to multiple sources of information, all of which are processed in an interactive network, which enables the system to maximize the opportunity for meaning creation (Libben, 2010). Under this view, semantic activation is not simply the final result of sub-lexical processing. Rather, it is fully integrated into the process from the outset.

Recent behavioural evidence supports this view that semantic activation is integrated from the outset of processing complex words, and critically, has set a benchmark for the time at which we should expect such effects to emerge in the brain. Schmidtke, Matsuki, and Kuperman (2017) presented an account which might constrain the time at which we should expect to see neural evidence of semantic activation. The authors used a survival analysis technique, which allows detection of the first point at which variables of interest affect some time-course outcome by considering an entire distribution of response latencies, not just the central tendency of that distribution. This can inform us on whether some manipulated variable affects all response latencies, or whether it has specific effects on fast or slow responses. Using this technique to analyse both response latencies and eye-tracking measures to complex words (specifically, true and pseudo-derived words such as *trucker* and *corner*, respectively), it was demonstrated that across word types, semantic effects emerge at the same time as, or even earlier than, morphological effects. Accordingly, the authors suggest that these effects must emerge in the brain prior to a behavioural benchmark of 120–140 ms. The present study, then, is in a unique position to answer this challenge raised by Schmidtke et al.: to demonstrate that in processing complex words, the brain is sensitive to semantic information as early as, or earlier than, their 120- to 140-ms benchmark.

1.3. The present study

In this study, we manipulated the transparency of both first and second constituents, resulting in four compound word groups (Table 1) and direct comparisons across multiple levels of transparency–opacity. Because compound words differ in their degree of transparency/opacity, and because transparency/opacity exists as a function of relations between constituents within the compound and the meaning of the whole word, it is possible to examine effects of word and constituent frequency and constituent transparency on processing. Accordingly, we tested the effects of word frequency and semantic transparency on behavioural measures (accuracy, RT) and on electrophysiological measures (ERP components P100, N170, P200, P300, and N400) at posterior lateral and central electrode sites. In order to maintain the variability inherent in word frequency, a continuous measure of word frequency was employed. We used multivariate by-item regression to analyse word length and word frequency as continuous variables, discrete dummy variables for semantic transparency, and individual words as cases to be entered into regression equations. We hypothesized that semantic transparency of the constituents would affect word reading at an early stage, and would affect P100 amplitude even after accounting for the effects of lower-level characteristics such as word length and word frequency. Transparency reflects the extent to which the meaning of the constituents is reflected in the meaning of the whole word, and thus, an ERP effect of constituent transparency reflects the latency by which meaning has been accessed for both the constituent and the full word.

Table 1
Stimulus words.

TT	OT	TO	OO
bedroom	chopstick	cardshark	deadline
coalmine	crowbar	doughnut	dingbat
daylight	dashboard	heatwave	fleabag
doorbell	godchild	jailbird	hallmark
farmyard	grapefruit	oddball	hogwash
fencepost	nickname	shoehorn	humbug
paintbrush	pothole	slowpoke	ragtime
rosebud	shortcake	sourpuss	rugrat
sailboat	strawberry	spoilsport	stalemate
schoolboy	sunfish	staircase	windfall

Note. T = transparent; O = opaque.

2. Materials and methods

2.1. Participants

Participants were 22 undergraduate students (15 women, 7 men; mean age = 20.5 years, 3 left handed). Three were pilot participants for whom only electrophysiological data – but not behavioural data – were recorded. Participants did not have any language deficits (e.g. dyslexia), attentional problems (e.g. ADHD), motor problems, psychiatric history, or other conditions affecting the functioning of the nervous system (e.g. acquired brain injury). All were native English speakers and had normal or corrected-to-normal vision.

2.2. Ethical procedures

Participants read and signed written informed consent and were compensated $10 or received course credit. Ethical clearance was received from the Brock University Research Ethics Board.

2.3. Stimuli

Eighty real English compound words and 80 novel compounds consisting of real English constituents were presented to participants in a lexical decision task. The nonwords were composed of real English constituents to ensure that the lexical decision was not overly easy, i.e. where a decision could be made based on word structure alone, and these were matched on word length. Only 40 of the real compound words, across four conditions, were pertinent to this study, where the 40 fillers were additional noun–noun compounds matched on word length and frequency. The 40 compound words analysed here were approximately matched for low-level orthographic characteristics such as neighbourhood size and bigram frequency. The variable of interest, semantic transparency, was defined as the meaning overlap between a compound constituent and its corresponding independent word. That is, in *bedroom*, one can discern the meaning by deconstructing the compound to its base constituents: a bedroom is a room in which a bed is housed. Opaque compounds include words such as *humbug*, where the whole word involves neither a bug nor something that hums. Words such as *strawberry* and *jailbird* lie in between, as they each have one constituent that conveys some consonant meaning, where *strawberry* may be more transparent than *jailbird* because the rightmost constituent is typically the head in English. A 'T' denotes a semantically transparent constituent, and an 'O' denotes a semantically opaque constituent. Categories did not significantly differ in average word length ($F(3, 36) = 2.70$, *n.s.*), although OO words were shortest (mean letters per word: TT, 8.2; OT, 8.4; TO, 8.3; OO, 7.3). Although each of the four groups of compound words only included 10 compounds (Table 1), these stimuli have consistently produced (behavioural) effects where TT words elicit fastest responses as indexed by RTs, followed by OT, TO, and OO words, where the general pattern is that words with a transparent second constituent are processed faster than words with an opaque second constituent (e.g. Libben et al., 2003; Libben & Weber, 2014).

2.4. Procedure

Six blocks of all 160 compound words were presented to participants. In a lexical decision task, participants made word–nonword judgments by pressing either a 'yes' or 'no' button. Each word was presented once per block, and the order in which the words were presented was randomized in each successive block. In addition to electrophysiological measures, participants were scored on RT and accuracy (whether they correctly indicated the lexicality of each word).

Participants performed the lexical decision task while electroencephalogram (EEG) was recorded. Stimuli were presented and responses were collected using E-Prime 1.2 (Psychological Software Tools, Inc., Sharpsburg, Pennsylvania) on a Dell monitor with a 75-Hz refresh rate. All stimuli were presented in white lowercase letters in Courier font on a black background in the centre of a computer monitor 60 cm from the participant. Task instructions were to press one button on a response box if the word was a real English word, and another button if it was not a word (response button options were counterbalanced across participants) followed by two practice trials. It was made clear that nonwords could be composed of two real words (e.g. watchpanic). This was confirmed by behavioural findings: accuracy was 78% for nonwords in the original experiment, and 89% in a behavioural follow-up (see footnote 2), suggesting that they could accurately distinguish words from nonwords, despite the productivity of English compounding.

Stimuli were presented for 250 ms with a pseudorandomized 400–1600 ms interstimulus interval. The relatively short presentation time and the highly variable interstimulus interval were employed in order to encourage sustained vigilance and quick reading, i.e. to discourage leisurely reading decomposition of the words. This procedure was adopted at the risk of relatively poor response accuracy due to quick decisions.

2.5. EEG recording

EEG recording was conducted using an elastic net with 128 silver chloride-plated electrodes embedded in sponges (Electrical Geodesics, Inc., Eugene, Oregon). All electrodes were referenced to the vertex (Cz) during recording and amplified by Net Amps 200 with a band-pass filter 0.01–100 Hz. EEG was sampled 500 times per second and impedances were maintained below 50 kΩ. Eye movements and blinks were monitored by electrodes placed below and beside both eyes. The EEG was re-referenced offline to the average of all sites.

Responses were considered valid if they were registered by the E-Prime program before the next stimulus appeared. In constructing ERPs, trials were defined by segmenting an epoch beginning 200 ms pre-stimulus onset for a baseline correction and ending 800 ms post-stimulus.

2.6. EEG processing, segmentation, and scoring

All preprocessing was performed in Matlab R2010b using functions from the open-source toolbox EEGLAB version 12.x (Delorme & Makeig, 2004) as well as in-house functions developed for conducting automated artefact removal on the Shared Hierarchical Academic Research Computing Network (SHARCNet). Full methodological details on EEG processing and ICA procedures for removing physiological artefact and periods of non-stationarity are available at https://git.sharcnet.ca/bucanl_pipelines/eeg_pipe_asr_amica.git (see also Desjardins & Segalowitz, 2013), and the preprocessed and scored data are also available in an online repository (Davis, Libben, & Segalowitz, 2018).

To account for potential individual word frequency effects, we segmented ERPs by word to create 40 single-item ERPs (see also Dien et al., 2003; Laszlo & Federmeier, 2011). Stimulus-locked ERPs were calculated relative to the onset of each target trial, and the baseline period was set as −200 to 0 ms prior to stimulus onset. The ERP for each of the 40 words was based on averaging a potential 132 trials (1 presentation per block × 6 blocks × 22 participants).

ERP scoring was conducted using ERPScore (Segalowitz, 1999). We took the average amplitude in 20-ms segments with 10-ms overlaps from stimulus onset (0 ms) to 500 ms. Each ERP component was scored at each scalp site using the largest average amplitude within defined time ranges – that is, component amplitudes were selected from the 20-ms segments – such that the P100 was defined as the most positive result in the timeframe of 70–150 ms, the N170 the most negative in 150–230 ms, the P200 as the most positive in 190–290 ms, the P300 as the most positive in 290–390 ms, and the N400 as the most negative in 360–500 ms. ERPs were scored at parietal-occipital scalp sites: three midline sites (Pz, Oz, and POz) and 26 sites surrounding the midline. Thus, there was a defined ERP component for each scalp site, but we only analysed the scalp site at which that component had the largest amplitude. For instance, while there was a P100 for all 29 sites, only two sites were actually analysed for each participant – those with the largest amplitudes on the left and right side for the specific component for each participant over the entire study. This scalp site was selected on the grand-averaged data across conditions before dividing the data by condition.

2.7. Data analysis

Behavioural data (RT, accuracy) were analysed by linear mixed effects regression, and ERPs were analysed by general linear models (nlme package in R; Pinheiro, Bates, DebRoy, & Sarkar, 2009; R Core Team, 2013). To simplify presentation of the analyses, separate regressions were modelled for left and right sites,[1] as well as for each ERP component (P100, N170, P200, P300, N400). Word length, bigram frequency (measured as both mean bigram frequency across all bigrams in the compound, as well as frequency of the critical boundary bigram at the junction of the two constituents, e.g. *dr* in *bedroom*, which might act as a cue for transparency), morphological family size (measured as both positional family size, i.e. how many times *bed* appears in initial position and *room* appears in final position, and compound family size, i.e. how many times each appears in either position), and word frequency were entered as continuous predictors, and constituent transparency was entered as a pair of dummy-coded categorical predictors. Word length, bigram frequency, and morphological family size were excluded in final presented models for simplicity of presentation, as they accounted for no significant variance in the ERP component amplitudes over and above word frequency and constituent transparency (word length: $R^2 = 0.000–0.013$; bigram frequency: $R^2 = 0.000–0.065$; morphological family size: $R^2 = 0.000–0.071$). Moreover, there were no significant correlations between word frequency and the transparency of either constituent (*r*s = 0.16–24, *p*s > .10), suggesting that any effects of transparency in the following analyses can be interpreted independently of word frequency.

3. Results

3.1. Behavioural findings

RTs were fastest when the second constituent was transparent ($t(141.6) = 4.039$, $p < .001$). RT was also faster with greater whole-word frequency ($t(36.2) = 3.801$, $p < .001$) and lower frequency of the second constituent ($t(35.5) = 2.445$, $p < .05$). Accuracy scores were relatively low for a lexical decision task, as expected, because of the brief presentation duration and variable interstimulus interval.[2] In

[1] There were no main effects of hemisphere in predicting ERP amplitudes. For highly lateralized components (e.g. the P100) there were interactions between hemisphere and our predictor variables in predicting ERP amplitude. This was not the case for the N400, which shows a more central-midline topographic distribution.

[2] To test our expectation that low accuracy scores were due to the rapid stimulus presentation, we conducted a short behavioral experiment ($N = 10$) with all parameters of the original lexical decision task held constant, except that stimulus presentation duration was doubled from 250 ms to 500 ms. As expected, accuracy scores were substantially higher (TT: 88%; OT: 92%; TO: 81%; OO: 80%; nonwords: 89%).

Table 2
Response time and accuracy differences by condition.

Condition	Response time *M* (*SD*)	Accuracy *M* (*SD*)
TT	598.72 (74.66)	0.789 (0.141)
OT	608.09 (85.55)	0.840 (0.131)
TO	627.57 (80.34)	0.710 (0.141)
OO	621.32 (91.92)	0.679 (0.173)

order to check whether individuals with very low accuracy biased the results, both analyses were repeated excluding participants with average accuracy scores under 70%, producing a similar pattern of behavioural and ERP results. Because case removal did not result in any changes to our findings, the complete dataset is reported for all analyses (Table 2).

3.2. ERP peak analyses

ERP component amplitudes (P100, N170, P200, P300, and N400; amplitudes presented in Table 3) were predicted in separate multiple regression analyses (general linear models) from whole word frequency entered on the first step and transparency factors entered on the second step. For brevity, we focus primarily on the P100 and N400 in discussing the results, but all findings are presented in Table 4. We also conducted analyses with individual constituent frequencies (e.g. of 'bed' and of 'room' separately) entered as predictor variables, but adding these variables generally did not confer additional explanatory power, and consequently, the simpler model with only whole word frequency as an initial predictor is presented here. Moreover, acknowledging that semantic transparency can also be considered as a continuous measure, we conducted the same analyses with continuous constituent transparency predictors normed by a different set of participants; the results were indistinguishable, and so we have retained our binary predictors in describing the present analyses.

Word frequency accounted for significant variance in P100 amplitude in zero-order correlations, as well as when first and second constituent transparencies were entered into the regression. First- and second-constituent transparency each accounted for significant variance in left-side P100 amplitude. Second-constituent transparency continued to affect later components. Word frequency did not significantly account for peak amplitudes of the N400, though the transparency of the second constituent accounted for significant unique variance in N400 amplitude (Table 4). Because we used partially overlapping time windows to define our ERP components, it is perhaps noteworthy that P300 amplitude also accounted for significant variance in N400 amplitude, and entering P300 first in the models reduced the effect of compound transparency on N400 amplitude to a trend ($p = .07$), suggesting that the two components may reflect the activity of a common underlying neural generator. Fig. 1 shows the ERP waveform comparisons by condition across six parietal-occipital scalp sites. There were no significant effects prior to the ascent of the P100, despite apparent visual divergence in the waveforms.

4. Discussion

We investigated whether transparency of the constituents of visually presented compound words affects ERP components. Given that transparency reflects the degree of congruency between the meaning of the constituent and the meaning of the whole word, an effect of transparency on ERPs could be taken to reflect that lexical-semantic access must have occurred for both items (constituent and full word) by the time the ERP component is generated. At a behavioural level, our results are largely consistent with prior work on compound transparency: words with transparent heads tended to be responded to faster than words with opaque heads (see e.g. Libben et al., 2003; Libben & Weber, 2014; for discussion, see also Libben, 2010). At a neurophysiological level, word frequency and constituent transparency both accounted for unique variance in P100 amplitude, independent of major lower-level characteristics (i.e. word length, bigram frequency, orthographic neighbourhood size). Lower frequency and opacity were associated with greater P100 amplitudes, and while the frequency factor continued its influence to the N170, the transparency factor continued to affect later components through to the N400, which showed increased amplitude facilitated by transparency. Our N400 findings are consistent with electrophysiological studies on visual compound word processing (e.g. Coch et al., 2013; El Yagoubi et al., 2008; Fiorentino et al., 2014; Vergara-Martínez et al., 2009), though it may be better to consider the N400 findings as reflecting an underlying neural generator common to the P300 and N400, as P300 also accounted for significant variance in N400 amplitude. The findings suggest that we extract and process semantic information about the word simultaneous with form-based information, and that this simultaneous access occurs as early as the P100 component. This would be predicted by Kuperman et al.'s (2009) interactive activation framework, which essentially adopts principles of form-then-meaning and meaning-then-form approaches, endorsing a form-*and*-meaning perspective, with the corresponding Schmidtke et al. (2017) framework suggesting that we should expect to see neural evidence of semantic activation in complex words prior to 120- to 140-ms post-stimulus. Indeed, this is what we have found in the present study. In the following, we unpack the theoretical implications of this finding.

The finding that word frequency modulates P100 amplitude was unsurprising and is consistent with previous work. Segalowitz and Zheng (2009) suggested that the larger P100 amplitudes for words than nonwords may be accounted for by bigram frequency effects. Hauk, Pattersonauk, et al. (2006) demonstrated that orthographically atypical words elicit more pronounced P100s than do typical words. Hauk et al. (2006a) and Hauk, Davis, Ford, Pulvermüller, and Marslen-Wilsonauk (2006b) also reported effects of frequency as early as 110 ms. What is more discordant from previous findings is the independent effect of constituent transparency, which cannot be accounted for by constituent frequency, and seems at odds with form-then-meaning approaches, given that morphological structure of compounds cannot easily be predicted by their form (as is the case for predictable suffixes). Importantly, our findings support word-internal integration of morphological and semantic information. Such rapid integration has been evidenced at the sentence level by Kim and Lai (2012), who found that slight deviations in word form at the end of a constraining sentence (e.g. substitute CEKE for CAKE following 'She measured the flour so she could bake a…') produce an enhanced P100 (~130 ms). Our findings extend this by showing that in compound words, much of this semantic work is done internally (i.e. transparency/opacity exists as a function of relations between constituents within the word), and the interaction between morphological and semantic characteristics can be observed as early as the P100.

An important concept here is that one constituent of the compound is the *head*, which determines the object class, whereas the other is the *modifier*. In English, the head is typically the rightmost constituent. The modifier restricts the meaning of the head, indicating that the compound word is some special kind of the head (e.g. a bedroom is a room in which a bed is located). TO and OO words, however, violate this semantic expectation. The present findings support Kuperman et al.'s (2009) multiple-route interactive model, which suggests that, in order to maximize opportunity for creating meaning, we gain simultaneous access to multiple sources of information about a word early in visual word processing. This model relies on Libben's (2006) maximization of opportunity principle, which indicates that readers will utilize all processing cues at their disposal. Here, the significance of both whole compound (frequency) and constituent (transparency) effects on the P100 indicates early access to whole compound words as well as both constituents. Under our view, constituent access is an intrinsic characteristic of compound processing, where whole word processing

Table 3
Average peak amplitudes for P100, N170, P200, P300, and N400.

Component	P100	N170	P200	P300	N400
Left					
TT	1.397 (0.90)	−2.009 (1.43)	1.140 (0.76)	1.784 (0.90)	−2.829 (0.72)
OT	2.184 (0.62)	−1.193 (0.66)	1.185 (0.69)	1.901 (0.72)	−2.441 (0.70)
TO	2.151 (0.98)	−0.848 (0.72)	1.541 (0.52)	2.440 (0.98)	−2.129 (0.73)
OO	2.963 (1.32)	−1.268 (0.84)	2.395 (1.37)	2.711 (0.56)	−1.914 (0.72)
Right					
TT	2.034 (0.71)	−1.172 (1.52)	1.324 (0.60)	2.333 (0.54)	−2.810 (0.58)
OT	2.271 (0.64)	−0.666 (0.95)	1.146 (0.40)	2.120 (0.54)	−2.422 (0.78)
TO	1.905 (1.30)	−0.742 (0.73)	1.672 (0.37)	2.641 (0.55)	−2.020 (0.77)
OO	2.213 (1.37)	−0.600 (1.21)	1.928 (1.79)	2.531 (0.83)	−1.828 (0.83)

Note. Average peak amplitudes (in μV) are presented with *SD*s in parentheses.

Table 4
Predicting left-side ERP amplitudes from whole word frequency and semantic transparency.

Component		Predictor	*F* change	*df*	*p*	R^2	R^2 change	*t*	*p*
P100	Step 1	WF	9.920	1, 38	.003	0.207	0.207	−3.150	**.003**
	Step 2	WF	4.354	3, 36	.001	0.361	0.154	−2.407	**.021**
		C1						2.154	**.038**
		C2						2.111	**.042**
	Step 3	WF	0.284	4, 35	.003	0.367	0.005	−2.441	**.020**
		C1						1.092	.282
		C2						1.063	.295
		C1 × C2						0.533	.597
N170	Step 1	WF	4.966	1, 38	.032	0.116	0.116	2.229	**.032**
	Step 2	WF	0.950	3, 36	.095	0.160	0.044	1.821	.077
		C1						0.224	.824
		C2						1.369	.180
	Step 3	WF	2.971	4, 35	.056	0.226	0.066	1.485	.146
		C1						1.402	.170
		C2						2.217	**.033**
		C1 × C2						1.724	.094
P200	Step 1	WF	2.804	1, 38	.102	0.069	0.069	−1.675	.102
	Step 2	WF	3.998	3, 36	.019	0.238	0.169	−0.957	.345
		C1						1.314	.197
		C2						2.559	**.015**
	Step 3	WF	2.809	4, 35	.014	0.295	0.057	−1.298	.203
		C1						−0.276	.785
		C2						0.608	.547
		C1 × C2						1.676	.103
P300	Step 1	WF	1.965	1, 38	.169	0.049	0.049	−1.402	.169
	Step 2	WF	3.697	3, 36	.034	0.211	0.162	−0.802	.428
		C1						0.570	.572
		C2						2.861	**.011**
	Step 3	WF	0.221	4, 35	.067	0.216	0.005	−0.872	.389
		C1						0.051	.959
		C2						1.498	.143
		C1 × C2						0.471	.641
N400	Step 1	WF	1.230	1, 38	.274	0.031	0.031	−1.109	.274
	Step 2	WF	3.930	3, 36	.039	0.205	0.174	−0.391	.698
		C1						1.212	.233
		C2						2.579	**.014**
	Step 3	WF	0.094	4, 35	.080	0.207	0.002	−0.316	.754
		C1						1.050	.301
		C2						1.985	.055
		C1 × C2						−0.306	.761

Note. Significant effects have *p*-values in bold. WF = word frequency; C1 = transparency of constituent 1; C2 = transparency of constituent 2.

always entails constituent activation and *vice versa*. Transparency only exists as a function of the relation between the meaning of constituents and that of the whole word, and thus, in order for early effects of constituent transparency to emerge, processing of the interaction between the whole form and the constituents is necessary. Further, the nature of this interaction may be rooted in competition or conflict: under the view that both constituent and whole-word properties of the compound are obligatorily activated, semantic opacity often engenders activation conflict (e.g. in *jailbird*, where the associates of *jail* and those of *bird* have not been associated over time). If conflict resolution is indeed the locus of behavioural effects (for discussion, see Libben, 2010, 2014) as well as the ERP results reported here, and opaque heads show greater competition than transparent heads, then this conflict must be linked to the semantic properties of compounds. This conflict could reflect either in-the-moment conflict between interacting constituents, accumulated semantic experience with the constituents as

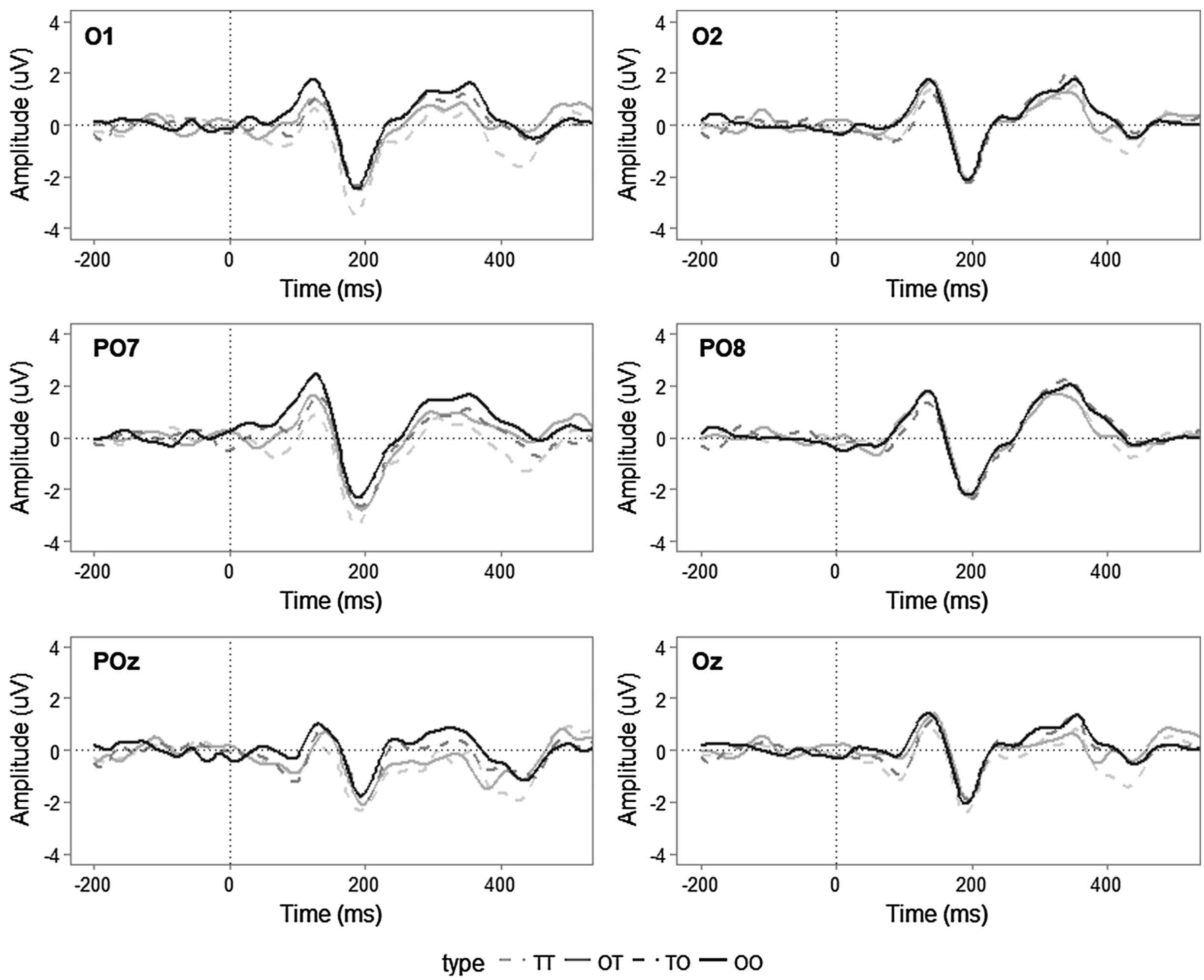

Fig. 1. Event-related potential waveforms for left, right, and midline occipital and parietal-occipital sites. Between-condition differences can be observed for the P100 at O1, for the P200 at POz, for the P300 at O1, and for the N400 at POz.

related or unrelated to the whole-word meaning, or perhaps most likely, both. Indeed, if semantic knowledge is taken to be an accumulation of an individual's lifetime experience, then these two alternatives are not mutually exclusive: in-the-moment processing should be reflective of accumulated experience with the constituents as being related or unrelated to the compound's meaning. Ultimately, the present results stand in contrast to form-then-meaning approaches (e.g. Fruchter & Marantz, 2015; Solomyak & Marantz, 2010) and instead support the notion that semantic information is also available at the earliest points of processing (e.g. Kim & Lai, 2012; Lewis & Poeppel, 2014; Schmidtke et al., 2017; Zauner, Gruber, Himmelstoβ, Lechinger, & Klimesch, 2014; see also Williams, Reddigari, & Pylkkanen, 2017).

Overall, the findings are supportive of the notion that obligatory decomposition plays a role in early visual word processing. This is demonstrated by the contribution of constituent transparency, and particularly first constituent transparency (which does not typically specify grammatical category in English compounds), to P100 amplitude. In accordance with the interactive activation framework (Kuperman et al., 2009) and maximization of opportunity principle (Libben, 2006), our results suggest that in addition to this obligatory decomposition, we extract and process semantic information about the word simultaneously. As indicated above, this would be predicted under the interactive activation framework. In its simplest form, it is an amalgamation of the form-then-meaning and meaning-then-form approaches, adopting instead a form-*and*-meaning approach to early comprehension processes. We maximize opportunity for meaning creation by using all processing cues available in complex words.

4.1. Limitations and future directions

The present study had several limitations. First, word frequency and other word-level characteristics were not explicitly matched between conditions, and thus we had to apply statistical adjustment during data analysis. Because English compounds are typically formed with the head as the right constituent, TT and OT compounds are more frequently occurring and more typical, and thus it may not be possible always to match word frequency across conditions of semantic transparency. Correcting this imbalance is an especially difficult goal, given the relative infrequency of OO and TO compounds, both in terms of occurrence in the language and usage. Although our TO and OO words were similar in average frequency to OT and TT words, their mean frequency values were skewed by two high-frequency words, 'deadline' for OO words and 'staircase' for TO words. Other characteristics of the words were also left uncontrolled, such as bigram frequency and grammatical category. We found that bigram frequency did not account for significant variance in ERP amplitudes, and it is unlikely that grammatical category was a critical factor, as a similar number of non-noun constituents seem present in OT, TO, and OO words, while TT words were predominantly noun–noun compounds. Nevertheless, future work may consider controlling the grammatical category of constituents.

Second, the experimental environment was set up to facilitate compound word recognition. That is, participants were exposed only to compound words, whether real (e.g. *deadline*) or nonwords (e.g. *cellorange*), throughout the course of the experiment. This experimental setup could have facilitated access to both constituents as well as to whole-word meanings, and particularly, relations between the two, since such relations would have been informative for rejecting non-words in the lexical decision task. However, this limitation may have been counteracted to some extent by repeating words six times, as repeated presentation would facilitate whole-word recognition. While we believe that the present study constitutes an important step, demonstrating that semantic activation of compound word constituents *can* occur prior to the 120- to 140-ms benchmark set out by Schmidtke et al. (2017), a next step will be to demonstrate that such activation *does*, in fact, occur in more naturalistic reading contexts.

Third, participants were uncharacteristically inaccurate in the lexical decision task. These stimuli have been used on several occasions (e.g. Libben et al., 2003; Libben & Weber, 2014), and have consistently generated higher response accuracies (e.g. 95% for OO compounds and 99% for TT compounds in Libben et al., 2003). This was probably due to the stimuli appearing for only 250 ms with an inter-stimulus interval of 400–1600 ms, ensuring that if anything, participants would be biased to read quickly and holistically, thus working against the hypothesis of the maximization of opportunity principle, and consequently strengthening our interpretation. Further, when the stimulus presentation time was increased to 500 ms, accuracy increased dramatically to 80–92%. The timing parameters used here are commonly used in, for instance, flanker tasks, in which 20–30% error trials are necessary in order to obtain stable error-related ERP components. Thus, accuracy scores in the 70–80% range appear reasonable given the complexity of the words. However, it would also be interesting to examine ERP components to reading our compound words at more *ad libitum* rates, even within the context of reading within a normal sentence context now that we know early semantic effects can be sought.

Finally, it may be that lexical decision does not permit the depth of processing necessary to posit semantic effects. However, lexical decision requires, at the very least, access to the mental representation of that word (Libben, 2009). It is important to note here that we were not comparing ERPs between words and non-words, but rather across different types of words. (In addition, even the foils consisted of compounds with real-word constituents.) The results indicated differences between these types of words not as a function of physical characteristics (e.g. length), and not only as a function of word frequency, but rather, differences emerged as a result of differences in transparency. This suggests that while there exists debate on the depth of processing elicited by the lexical decision task, we were able to elicit differences in processing as a function of the semantic properties of words.

4.2. Conclusions

The present findings address core issues on the time course of lexical-semantic access and the nature of morphological processing. Specifically, we demonstrated that ERP components as early as the P100 are sensitive to lexical-semantic variables, in support of recent findings suggesting early access to meaning and contrary to form-then-meaning approaches to complex visual word processing. Further, constrained by Schmidtke et al. (2017) neurophysiological benchmark of 120 ms, the findings lend support for the multiple-route interactive model (Kuperman et al., 2009) for compound word processing, as readers appear to have access to all available cues – the whole word, its constituents, and the interaction between whole form and constituent – at the earliest stages of processing. The findings, while novel, fit with the ever-growing trend in the literature implicating the P100 in very early processing, demonstrating that there is access to word-specific characteristics (both lexical and semantic) as early as the P100 ERP component.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2018.12.006.

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