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The Role of Semantic Transparency in the Processing of Spoken Compound Words

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The question of whether lexical decomposition is driven by semantic transparency in the lexical processing of morphologically complex words, such as compounds, remains controversial. Prior research on compound processing has predominantly examined visual processing. Focusing instead on spoken word word recognition, the present study examined the processing of auditorily presented English compounds that were semantically transparent (e.g., *farmyard*) or partially opaque with an opaque head (e.g., *airline*) or opaque modifier (e.g., *pothole*). Three auditory primed lexical decision experiments were run to examine to what extent constituent priming effects are affected by the semantic transparency of a compound and whether semantic transparency affects the processing of heads and modifiers equally. The results showed priming effects for both modifiers and heads regardless of their semantic transparency, indicating that individual constituents are accessed in transparent as well as opaque compounds. In addition, the results showed smaller priming effects for semantically opaque heads compared with matched transparent compounds with the same head. These findings suggest that semantically opaque heads induce an increased processing cost, which may result from the need to suppress the meaning of the head in favor of the meaning of the opaque compound.

Keywords: morphological processing, compounds, semantic transparency, spoken word recognition, primed lexical decision

Supplemental materials: https://doi.org/10.1037/xlm0001132.supp

The representation of morphological structure in the mental lexicon and the extent to which morphological processing is constrained by semantic transparency continue to be major lines of research in psycholinguistics (e.g., Feldman & Bentin, 1994; Gagné et al., 2016; Marslen-Wilson et al., 1994; Rastle et al., 2000; Smolka et al., 2014; Taft, 2004). Compound words provide an important window on lexical processing and representation. Compounding is a word formation process that involves the combination of at least two open-class morphemes to form morphologically complex words (e.g., *tea* can combine with *cup* to form *teacup*). In this article, we focus on English two-part compounds, in which the second constituent forms the *head* of the compound, specifying the grammatical category of the whole compound, while the first constituent modifies the head, thereby specifying its meaning.

Compound words may be semantically transparent or semantically opaque. In opaque compounds, the meaning of at least one constituent morpheme is not consistent with the meaning of the whole word. For instance, *payroll* and *lawsuit* are partially opaque, as there is no transparent meaning contribution of the head constituents *roll* or *suit* in these compounds. It is also possible that only the head constituent is transparently related to the full compound, whereas the modifier constituent is not. This is the case in *pothole* and *strawberry*, in which there is no meaning of the modifier constituents *pot* or *straw*. In a similar vein, both constituents may be opaque in meaning, as in *humbug* and *stalemate*. We refer to these types of compounds as transparent–opaque (TO), opaque–transparent (OT) and opaque–opaque (OO), respectively. Finally, when the meaning of the entire compound can be derived from the combination of the meaning of its constituents, as in *farmyard*, the compound is semantically transparent (TT).[1]

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The supplemental material, raw data, and analysis code for all experiments are available on the Open Science Framework (https://osf.io/upefr/).

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[1] Even the meaning of transparent compounds often cannot be unambiguously predicted from the meanings of the modifier and head constituents. For example, a *butterfly net* and a *tennis net* are both types of nets, but the modifier's relation to the head differs: a *butterfly net* is used to collect butterflies, a *tennis net* is used to play tennis (cf. Spalding & Gagné, 2014). Moreover, a *butterfly net* can be used to collect insects more generally, not just butterflies.

A wealth of studies have addressed the processing and representation of morphological structure in different types of words—including compounds—in the visual modality. Conversely, very few studies have examined the way in which morphologically complex *spoken* words are processed. The importance of examining morphological processing in the intramodal auditory modality has been highlighted in a number of studies (see, e.g., Bacovcin et al., 2017; Creemers et al., 2020; Goodwin Davies & Embick, 2020; Gwilliams & Marantz, 2015; Koester et al., 2004; Wilder et al., 2019). As can be seen in works like these, auditory processing and visual processing sometimes differ in ways that allow for different (and in certain cases, converging) perspectives on how words are represented and processed.

A key difference between the two modalities concerns how information about the word to be processed becomes available. In contrast to visual processing, the acoustic signal unfolds over time in spoken word processing. The temporal differences between the visual and auditory modality may have important consequences for lexical access in general and compound processing in particular. For compound words, the constituents that make up the compound are perceived serially in spoken-word processing, with the modifier being presented prior to the presentation of the head constituent in English. In contrast, both compound constituents appear simultaneously in visually presented words. As we will review below, examining the auditory processing of materials that have traditionally been studied in the visual modality has the potential to both provide converging evidence with prior results and to identify new insights that have not been detected in visual studies.

In this article, we examined the effects of semantic transparency on the processing of spoken English compounds. We report the results of three priming experiments that manipulated the semantic transparency of modifier and head constituents. Our focus is on two sets of questions: first, whether the processing of spoken compound words is constrained by semantic transparency; and second, whether transparency and opacity produce different effects depending on whether they are a property of the head or modifier constituents.

Semantic Transparency

Many priming studies concerned with the visual processing of compound words have examined to what extent semantic transparency affects morphological processing. The majority of visual primed lexical decision studies provide evidence that constituent repetition priming occurs for both transparent and opaque compounds (cf. Libben, 2014). Although there are some studies that have argued that priming effects can be obtained for fully transparent compounds, but not for (partially) opaque ones (e.g., Isel et al., 2003; Sandra, 1990; Zhou & Marslen-Wilson, 2000), most studies have reported at least some level of priming for opaque compounds as well.

Shoolman and Andrews (2003), for instance, reported significant priming effects regardless of semantic transparency in a visual masked priming paradigm. Transparent (e.g., *bookshop*) and partially opaque (e.g., *jaywalk*) compounds were both primed by their constituents (e.g., *book*, *shop*, *jay*, *walk*). Fiorentino and Fund-Reznicek (2009), building on Shoolman and Andrews (2003), but using compounds as primes, also provided evidence for morphological segmentation during early visual word recognition of compounds that happens irrespective of semantic transparency. These results follow from an account in which all compounds are immediately decomposed into their constituent morphemes, followed by a look-up of the meaning of these constituents, which are then combined again into the compound (see also Fiorentino & Poeppel, 2007). Under this approach, semantically opaque words are expected to undergo morphological decomposition to roughly the same extent as semantically transparent compounds.

In a series of visual masked priming experiments with varying mask and prime durations, Gagné et al. (2018) provided additional evidence that the language system recovers embedded morphemes and attempts to create a morphemic structure whenever potential morphological representations are available. They reported that opaque compounds facilitate the recognition of their embedded first constituent (e.g., *pineapple* → *pine*), which again suggests that morphological decomposition occurs also during the processing of compounds with opaque constituents. In addition, Gagné et al. (2018) showed that even pseudocompounds (such as *carpet*, in which *car* and *pet* do not function as a morphemes), resulted in the activation of the initial embedded word (*car*). In contrast to opaque compounds, exposure to pseudocompounds resulted in significant inhibition of the target *car*. These findings suggest that the processing system establishes a morphological structure for *all* compounds, including opaque compounds and even pseudocompounds; however, this may lead to a processing cost when the established structure is incompatible with the true morphemic structure of the word (see also Chamberlain et al., 2020).

These effects could be argued to result from an early stage of morpho-orthographic decomposition probed specifically by visual masked priming, similar to the *corner* → *corn* priming effects found in masked priming (e.g., Rastle & Davis, 2008). However—and interestingly—priming effects for semantically opaque compounds have also been reported for visual overt (nonmasked) priming studies. Zwitserlood (1994; Experiment 1), for instance, found significant priming effects regardless of semantic transparency. Visually presented Dutch compounds that were fully transparent or partially opaque both facilitated recognition of their first and last constituents. In contrast, no facilitation was obtained from mere orthographic overlap. Similarly, Libben et al. (2003; Experiment 2), in an overt visual priming study, reported priming for both transparent (*carwash*) and opaque (OT: *strawberry*; TO: *jailbird*; OO: *hogwash*) compound targets by their first and second constituents in English. Smolka and Libben (2017) reported priming effects regardless of semantic transparency in a series of experiments with German compounds, testing both modifier transparency (T: *Hund* [*dog*] → *Hundeauge* [*dog's eye*]; O: *Huhn* → [*hen*] *Hühnerauge* [literally *hen's eye*; *corn/clavus*]) and head transparency (T: *Esel* [*donkey*] → *Lastesel* [*pack donkey*]; O: *Esel* [*donkey*] → *Drahtesel* [literally *wire donkey*; *bicycle*]).

In line with these results, Libben (2006) argued that semantic opacity does not diminish constituent activation at all, and that all possible morphological representations are activated regardless of semantic transparency. With opaque compounds, the semantic representations activated by the semantically unrelated morpheme do not overlap with the semantic representations activated by the compound. The resulting mismatch may require resolution through the inhibition of the inappropriate semantic activation (Libben & Almeida, 2002; Libben et al., 2004). This inhibition may explain why some priming studies appear to show no priming effects for semantically opaque compounds. In a similar vein, Gagné and Spalding (2014) argued that meaning composition plays a role in reported differences between the processing of opaque and transparent compounds (see also Ji et al., 2011). Frisson et al. (2008) further proposed that opaque compounds might be more difficult to process than fully transparent ones, since the compound meaning that results from combining the meaning of the constituents is in conflict with the stored whole-word meaning.

Modifiers and Heads

In addition to the effects of semantic transparency, priming studies have also pointed to a possible difference in the processing of modifiers and heads (or of first and second constituents, as discussed below). In an early lexical decision study by Taft and Forster (1976), it was argued that compound words are accessed via their first syllable, and that, therefore, the first constituent in a compound word enjoys a special status. The authors reported that compound nonwords whose first constituent is a word (e.g., *footmilge*) took longer to classify as nonwords than compound nonwords whose first constituent is not a word (e.g., *trowbreak*).

Later constituent priming studies revealed an important role of the second constituent in addition to the first constituent (e.g., Duñabeitia et al., 2009; Fiorentino & Fund-Reznicek, 2009; Shoolman & Andrews, 2003). The results from a masked priming study on Basque compounds, for instance, suggested that constituent activation is position-independent (Duñabeitia et al., 2009). Significant priming was obtained with compound primes that shared either the first (e.g., *milkshake*) or the second (e.g., *postman*) constituent with a compound target (e.g., *milkman*). Yet others reported a dominant role of the second constituent (Isel et al., 2003; Juhasz et al., 2003). Juhasz et al. (2003), for instance, found facilitatory effects of the frequency of the second constituent in English compounds in several experimental paradigms, but not of the first constituent.

A related question is whether semantic transparency affects the processing of heads and modifiers similarly or whether the effects of opacity may be different for heads and modifiers. The head determines the lexical category of the compound (e.g., *to* $cherry_N pick_V$ denotes a verb and *a* $hot_A dog_N$ denotes a noun) and, at least in the case of transparent heads, determines the kind of objects that the compound denotes (e.g., a *farmyard* is a type of *yard*, not a type of *farm; for* further discussion, see Gagné et al., 2020). Therefore, one could predict that semantic transparency may affect heads differently from modifiers. In a study by Libben et al. (2003), as mentioned in the preceding text, all four possible categories of semantic transparency were included: fully transparent compounds (TT: *car/wash* → *car-wash*), partially opaque compounds (OT: *straw/berry* → *strawberry*; TO: *jail/bird* → *jailbird*), and fully opaque compounds (OO: *hog/wash* → *hogwash*). Although the results showed that all compound types could be facilitated by prior presentation of their constituents, the results also indicated that the compounds with opaque heads (OO and TO) resulted in greater response times than the compounds with transparent heads (OT and TT). The response times to OT and TT compounds were not significantly distinct from each other.

The findings by Libben et al. (2003) suggest that the occurrence of the opaque constituent as either the head or the modifier matters: compounds with an opaque head were processed differently from compounds with a transparent head, while this difference did not occur for modifiers. Note, however, that it is unclear whether this is an effect of headedness (modifier vs. head) or of position (first constituent vs. second constituent). In a recent study, Libben et al. (2018) argued in favor of the former and showed that priming effects for compounds are independent of constituent ordering, as they found a similar pattern for Hebrew head-initial compounds as was previously reported for German head-final compounds.[2] However, it is still important to consider the possibility that a difference between constituents may (in part) be driven by the linear order of the constituents, rather than a distinction between modifier and head constituents.

On this point, it is relevant to note that in a typical priming paradigm that employs morphologically complex primes and simplex targets, constituent targets (M) follow compound primes (MM). Under this presentation order, head targets occur immediately after their occurrence in the prime (e.g., *farmyard* → *yard*). In contrast, with modifier targets (e.g., *farmyard* → *farm*), the head constituent (i.e., *yard*) occurs between the repeated constituents. The reverse holds when using constituent primes (M) and compound targets (MM), in which case the repeated constituents are linearly adjacent with modifier primes (e.g., *farm* → *farmyard*) but not in the case of head primes (e.g., *yard* → *farmyard*), for which the modifier constituent intervenes. In each case, the nonrepeated constituent may function as an "intervener" between primes and targets. As it is frequently reported that intervening items reduce priming effects (see, e.g., Kouider & Dupoux, 2009; Stanners et al., 1979; Wilder, 2018; Wilder et al., 2019), it is possible that the linear order of compound constituents, rather than their status as head or modifier, is responsible for differences reported in work like Libben et al. (2003; for discussion, see also Myers, Derwing, & Libben, 2004). If the linear order of the constituents causes differences in priming effects between modifiers and heads, this should be particularly clear in the auditory modality due to the incremental nature of the speech signal.

Auditory Processing of Compounds

Although many priming studies have addressed the visual processing of compound words, relatively few have examined their auditory processing. This means that most of our knowledge about the processing of compounds is based on visual, or orthographic, word processing. Exceptions are studies that employed a cross-modal paradigm, in which the primes, but not the targets, are presented auditorily (e.g., Isel et al., 2003; Pratarelli, 1995; Zhou & Marslen-Wilson, 2000). In addition, a series of neurophysiological studies has examined auditory compound processing, but without using the primed lexical decision paradigm (e.g., Koester et al., 2007; Koester et al., 2004; Koester et al., 2009; MacGregor & Shtyrov, 2013). Examining the processing of compound words in the auditory modality may offer different types of insights. On the one hand, results from spoken-word processing may provide converging evidence with visual results, which would suggest that the

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[2] Studies on Romance compounds, which can be either head-initial or head-final, have further addressed this issue for transparent compounds (see e.g. Duñabeitia et al., 2007; El Yagoubi et al., 2008; Jarema et al., 1999; Marelli et al., 2009).

nature of compound processing and representation in the mind generalizes across modalities. On the other hand, the results may diverge from visual results because of the temporal differences between the modalities, and thereby offer new perspectives on existing or novel issues.

Starting with the latter point, there are several reasons to suspect that visual and auditory processing of compound words may differ. First, in contrast to visual processing, with spoken word processing the acoustic signal unfolds over time and is incremental in nature. For compound words, this means that the constituents that make up the compound are perceived serially (Koester et al., 2007), while both compound constituents appear simultaneously in visually presented words. These temporal differences may have important consequences for lexical access (see, e.g., Balling & Baayen, 2008, 2012; Marslen-Wilson, 1984). In addition, the prosodic cues available in the auditory modality may influence processing. It has been argued, for instance, that the duration and the fundamental frequency of the first constituent in German forms a crucial prosodic cue for determining whether the first constituent is the onset of a compound word or whether it represents a separate monomorphemic word (e.g., Isel et al., 2003; Koester et al., 2004; see also Vogel & Raimy, 2002). Prosody has also been shown to signal the constituent's head or nonhead status in German (Koester et al., 2009). For English, the difference in stress between modifiers and heads could be another contributor to asymmetries between modifier and head positions in the auditory modality (typically, the modifier is stressed but exceptions exist, see, e.g., Giegerich, 2009). This asymmetry does not occur in compounds that are presented orthographically.

Despite these differences between the modalities, some studies on compound processing have shown similar results in the auditory modality as in the visual modality. This suggests that the nature of compound representations in the mind may generalize across modalities. Koester et al. (2004), for instance, manipulated the syntactic gender agreement between a determiner and the initial compound constituent (the modifier constituent), and between a determiner and the last constituent (head) during auditory processing using event-related brain potentials (ERP). Gender-incongruent constituents elicited a left-anterior negativity for both constituents and with both semantically transparent and opaque compounds. The results showed that syntactic gender information of modifier constituents is available, which was taken as evidence that both transparent and opaque compounds are decomposed during auditory word processing, similar to what has been shown for visual processing.

In another direction, Schmidtke et al. (2018) examined the role of competition between relational meanings (e.g., *seaweed* as "weed LOCATED IN sea" or "weed FROM sea") across visual and auditory compound word processing. They showed that compounds that have a greater set of competing relational meanings result in longer latencies in an auditory (unprimed) lexical-decision task. Crucially, the same results were obtained in two additional experiments that used a visual lexical-decision task. These findings provide additional evidence that at least certain aspects of compound recognition do not differ based on whether compounds are recognized through auditory or visual input. In addition, given that relational interpretations need the constituents to constitute the relations, this suggests that the individual constituents may be accessed in both visual and auditory processing of compounds.

The Current Study

In the current study, we report the results of three priming experiments with English compound words that examined the effects of semantic transparency on modifier and head constituents in the auditory modality. All three experiments used an overt constituent priming paradigm, paired with continuous lexical decision. The experiments were designed to address two main aims.

The first is to determine whether prior activation of a compound constituent affects the subsequent processing of that constituent in the auditory modality and to what extent these effects are influenced by the semantic transparency of a compound. We hypothesized that if compounds are decomposed into their constituent words in the auditory modality, significant priming effects should be obtained regardless of the semantic transparency of the compound. To that end, we examined whether priming effects for partially opaque compounds (OT, TO) are different from transparent (TT) compounds in spoken word processing. As noted in the preceding text, this differs from the majority of studies on compound recognition, which have examined compound processing in the visual modality.

The second aim of the article is finer grained and asks whether semantic transparency affects the processing of heads and modifiers differently. We hypothesized that, if the modifier/head distinction that is posited for compounds plays a role in their processing, we should be able to identify processing differences between modifier and head constituents when their transparency is manipulated. In particular, on account of the role the head plays in determining the meaning of the entire compound, opaque heads may be expected to induce an increased processing cost relative to transparent heads, while opacity might have less of an effect on the processing of modifiers. To that end, we compared the processing of two partially opaque conditions, that is, opaque compounds that have an opaque modifier (OT) and those that have an opaque head (TO). Note that, in much prior work, 'opacity' has been taken as a property of the full compound, hence combining all relatively semantically opaque compounds into a single category and using a binary classification of transparent/opaque compounds. In contrast, when distinguishing the opacity of the head and modifier within a compound, it becomes possible to examine whether effects of transparency differ depending on the locus of the opaque constituent in OT and TO compounds (cf. Libben et al., 2003).

To address the question concerning whether potential differences between heads and modifiers are driven by linear factors or by the different roles that modifiers and heads play, we used compounds both as primes (Experiment 1) and as targets (Experiment 2). This comparison allowed us to test both heads and modifiers with interveners (e.g., *hole* → *pothole*; *pothole* → *pot*) and without them (*pothole* → *hole*; *pot* → *pothole*). This way, the processing effects of both compound constituent type (head vs. modifier) and linear order of prime/target could be examined.

In summary, the hypotheses to be examined are as follows:

> *Hypothesis 1:* If compounds are decomposed into their constituent words in the auditory modality, significant priming effects should be obtained regardless of the semantic transparency of the compound.

> *Hypothesis 2:* If the modifier/head distinction that is posited for compounds plays a role in their processing, processing differences between modifier and head constituents should occur when their transparency is manipulated. In particular, opaque heads should induce an increased processing cost relative to transparent heads, on account of the role the head plays in determining the meaning of the entire compound, while opacity will have less of an influence for modifiers.

The following sections present results from three experiments that make use of the same sets of English two-part compound words. Experiment 1 examined transparent (TT) and partially opaque (OT/TO) compound priming effects on the recognition of modifier and head constituents. Experiment 2 reversed the order of primes and targets, to examine the effects of head versus modifier priming in a within-target design. Finally, Experiment 3 examined the differences in processing of head constituents in partially opaque (OT and TO) and matched transparent (TT) compounds in more detail.

Experiment 1

Experiment 1 tested whether the presentation of a compound facilitates recognition of its constituent morphemes with transparent (TT) and partially opaque (OT/TO) compounds. Both modifier and head constituents were used as targets, which was treated as a between-participants factor, such that each participant saw either modifiers or heads as the target but not both. Experiment 1a tested priming of modifier constituents, using the compound as the prime and the modifier constituent as its target (e.g., *bedroom → bed*). Experiment 1b tested priming of head constituents (e.g., *bedroom → room*). All primes and targets were presented auditorily.

Method

Participants

Participants were undergraduate students at the University of Pennsylvania, who reported to being native speakers of English. A total of 122 participants took part in Experiment 1, 62 in Experiment 1a and 60 in Experiment 1b. A power calculation in G*Power (Faul et al., 2007) indicated that with 12 items per condition, a sample size of $n = 15$ was sufficient to detect a main effect of condition with an effect size f of at least .25 (a medium effect size) with 80% power. To account for the interaction with prime type (related/unrelated), we included twice as many participants per cell, therefore including four times as many participants. This led to the goal of obtaining a total sample size of at least $n = 60$ per subexperiment. Ethical approval for the study was provided by the Institutional Review Board at the University of Pennsylvania. Participants provided informed consent and received course credit as compensation for their participation.

Materials

Primes were English noun compounds that were partially opaque (TO or OT) or fully transparent (TT), as illustrated in Table 1. We included 12 prime–target pairs per condition, with the modifier (Experiment 1a) or head (Experiment 1b) constituent as the target. The majority of the compounds consisted of two monosyllabic constituents, but in some cases a disyllabic constituent was included. Each compound prime was matched to an unrelated control compound, on the basis of frequency and number of syllables, such that, for instance, *crowbar* (frequency: 1.76) was matched to *lifeguard* (1.75), and *butterfly* (2.27; disyllabic modifier constituent) to *database* (2.36). A full stimulus list can be found in the online supplemental material. Frequencies were extracted from the SubtLex-US database (Brysbaert, New, & Keuleers, 2012), and are summarized in Table 2.

Table 1

Conditions and Sample Critical Items in Experiment 1a, in Which the Target is Formed by the Modifier Constituent, and Experiment 1b, in Which the Target is Formed by the Head Constituent

	Prime type		Target type	
Condition	Related	Unrelated	Modifier	Head
OT	*pothole*	*swordplay*	*pot*	*hole*
TO	*airline*	*earthquake*	*air*	*line*
TT	*farmyard*	*smokescreen*	*farm*	*yard*

Note. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent.

To establish the semantic relatedness between primes and targets, a norming study was conducted with candidate prime–target pairs that differed in semantic relatedness from fully opaque to fully transparent. Semantic relatedness scores were obtained for both modifier and head constituents of the compounds. Native speakers of English ($n = 40$) were asked to rate the semantic relatedness of word pairs on a seven-point rating scale, with 1 = *completely unrelated in meaning* and 7 = *highly related in meaning*. The pretest was conducted through Qualtrics (https://www.qualtrics.com). Participants were undergraduates at the University of Pennsylvania and were compensated for their time with course credit. They were given the option to leave the rating scale empty in case they were not familiar with a word in the word pair. This information was later used to exclude certain pairs from the critical items (e.g., *cardshark*, *turncoat*, *fleabag*; see also Footnote 3).

The mean scores for the modifier and head constituent in each compound were used as criteria for including items as critical items in the experiments, and for grouping them into the relevant conditions (OT, TO, TT).[3] Constituents were categorized as *opaque* (O) when they had a mean semantic score that was lower than 3, and as *transparent* (T) when they had mean semantic score that was higher than 4. This means that, for instance, a compound for which the modifier constituent had a mean score of 2 and the head constituent had a main score of 5 would be categorized as OT, while a compound for which the modifier constituent had a mean score of 6 and the head constituent had a main score of 1 would be categorized as TO. These criteria led to the inclusion of 12 items per condition, for which the mean semantic scores are given in Table 2.

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[3] We intended to examine OO compounds in our study as well and included potential OO compounds in the norming study. However, we decided against including OO compounds for several reasons. First, only 10 compounds satisfied our inclusion criteria for a classification as OO (i.e., a mean semantic score of <3 for both constituents). Second, for these compounds, many participants indicated that they were not familiar with the compound or either of its constituents. Examples of such compounds were *humbug*, *ragtime*, and *rugrat*. And finally, the head constituents for the OO compounds had a higher mean score (2.34) than the O constituents in the other types of compounds (OT: 1.85; TO: 1.91).

Table 2

Stimulus Characteristics (Means and Standard Deviations, in Parentheses) of Primes and Targets in Experiment 1

	Frequency prime		Frequency target		Semantic score	
Condition	Related	Unrelated	Modifier	Head	Modifier	Head
OT	1.67 (0.48)	1.64 (0.48)	2.91 (0.53)	3.34 (0.35)	1.85 (1.20)	5.27 (1.63)
TO	1.74 (0.52)	1.56 (0.70)	3.10 (0.57)	3.10 (0.48)	5.50 (1.62)	1.91 (1.23)
TT	1.63 (0.50)	1.62 (0.44)	3.19 (0.48)	2.89 (0.61)	5.84 (1.51)	5.80 (1.29)

Note. Frequencies (Lg10CD) were extracted from the SubtLex-US database (Brysbaert et al., 2012). Semantic relatedness scores reflect ratings on a 7-point scale (1 = *completely unrelated in meaning*; 7 = *highly related in meaning*). OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent.

One-way analyses of variance (ANOVAs) were performed on mean semantic scores for modifier and head constituents. For the semantic relatedness between the compounds and their modifier constituents, the ANOVA showed highly significant differences between conditions, $F(2, 33) = 252.3$, $p < .001$. Post hoc testing with Tukey's test shows that the TO and OT ($p < .001$), and the TT and OT ($p < .001$) conditions were significantly different. No significant difference was found between TT and TO ($p = .220$). For the semantic relatedness between the compounds and their head constituents, the ANOVA again showed highly significant differences between conditions, $F(2, 33) = 132.7$, $p < .001$. Post hoc testing with Tukey's test shows that TO and OT were significantly different ($p < .001$), as were TT and TO ($p < .001$). No significant difference was found between TT and OT ($p = .121$).

For the purpose of the lexical-decision task, we included a total of 232 filler and pseudoword items. We included 80 filler words, 40 of which were monosyllabic and monomorphemic words, 20 were compound words, and 20 words were derivationally complex words (e.g., *brightness*). We ensured that none of the fillers (and the unrelated primes) had constituents that occurred in the critical items. We also included 152 pseudowords, of which half were monosyllabic and half were disyllabic with stress on the first syllable, to resemble the stress in compound words. Some of the disyllabic pseudowords had a first syllable that forms an existing word (e.g., *jeep–RAHST*), to ensure that participants could not make a lexical decision based merely on the first part of the pseudowords. In total, each participant saw a total of 304 items; critical items (including the unrelated primes) made up 23.78%. Fillers and pseudowords were randomly combined to create prime–target filler pairs.

Apparatus

The stimuli were recorded by an adult male native speaker of American English in a sound attenuated booth, using a high-quality microphone. Soundfiles were segmented using Praat (Boersma & Weenink, 2015) and normalized to a peak amplitude of 70 dB SPL. The task was implemented in the experimental presentation software Ibex (Drummond, 2013), using the PennController (Zehr & Schwarz, 2018) experiment toolkit.

Procedure

A continuous lexical-decision task was used, in which participants made a lexical decision to both primes and targets. As the experiment was run online, participants used their own auditory presentation equipment and responded using their keyboard. The experiment started with a sound check in which participants were asked to test whether their audio system worked by playing a file. Participants were then instructed that they would hear existing and nonexistent English words, and that they had to make a lexical decision to each word as quickly and accurately as possible: "When you hear a sound, please decide as quickly and accurately as you can whether the sound is a real word or not a real word (e.g., a nonsense word or a sound) of English." Participants were instructed to press the *F* key using their left index finger for "nonword" and the *J* key using their right index finger for "word." The reminder "F: nonword and J: word" also appeared on the screen during each trial. Participants were asked to complete the experiment in one sitting. The experiment lasted 13 min on average per participant in Experiment 1a, and 16 min on average in Experiment 1b.

Both subexperiments consisted of two lists, with related and unrelated primes to the same target rotated on different lists. Participants were randomly assigned to either list. The task had a random interstimulus interval (ISI) between 800 ms and 1,000 ms. The ISI was measured from the end of the sound file or participant response, whichever was later. The experiment consisted of four blocks with the possibility for a self-administered break after each block, and a practice phase of 14 items at the beginning of the experiment. Throughout the experiment, stimuli presentation was pseudorandomized such that the critical prime–target pairs were dispersed evenly among the resulting four blocks, and consecutive trials did not involve critical items.

Analysis

The data were analyzed as follows. Responses were coded for response type (word/nonword) and response time (RT; measured in ms from the onset of the sound file). Differences in duration of the target sound files were included as a predictor in the model. A total of 5 participants were removed due to an overall low accuracy across all stimuli (<75%) in Experiment 1a, and a total of two participants in Experiment 1b. In Experiment 1a, one participant was removed for taking unreasonably long to finish the experiment. Two further participants were excluded from Experiment 1b as they reported that they were not native speakers of English.

For both subexperiments, trials with incorrect responses to primes or targets were discarded (204 observations or 10.12% in Experiment 1a; 250 observations or 12.40% in Experiment 1b). Targets with outlier RTs (<100 ms and >2,000 ms) and targets for which the prime had an outlier RT were also discarded (52 observations in Experiment 1a and 81 in Experiment 1b). We then combined minimal a priori data trimming with postfitting model criticism (Baayen & Milin, 2010). The RT data were log-transformed, and removal of outliers was done for individual participants and individual items for which Shapiro-Wilk's tests for normality showed nonnormal distributions. This led to the removal of 60 datapoints in Experiment 1a and 43 in Experiment 1b.

We analyzed effects on log-transformed RT with linear mixed-effects models, using the lme4 package (Version 1.1–21; Bates et al., 2015) in the R environment (Version 3.6.0; R Core Team, 2016). We fitted two models, one for each subexperiment. In both models, we included random intercepts for participants, targets, and primes. Fixed effects were condition (OT/TO/TT) and prime type (related/unrelated) and their interactions. Condition was coded with Helmert contrasts, such that the first contrast codes the difference between the partially opaque OT and TO conditions (coefficients: OT = -1, TO = 1, TT = 0), and the second contrast tests the difference between the transparent TT (2) condition and the mean of both partially opaque conditions (both –1). prime type was coded using sum coding with coefficients –.5 for related primes and .5 for unrelated primes. Post hoc comparisons were performed with emmeans (Length et al., 2018). We compared the levels of prime type within each level of condition.

We further included trial number to control for effects of learning or fatigue, and log-transformed prime RT and ISI (as a continuous variable, measured from the end of the sound file or participant response, whichever was later) to control for the effect of the latency at the preceding prime and the time preceding the target-on-target recognition. To control for the properties of the stimuli, we included target frequency, prime frequency, and target duration. The continuous variables were centered. Model criticism was performed on the full models to identify overly influential outliers (Baayen & Milin, 2010). The models were refitted after excluding data points with absolute standardized residuals exceeding 2.5 standard deviations. This led to the removal of 46 datapoints (2.71%) in Experiment 1a, and 36 datapoints (2.19%) in Experiment 1b. The results of the final models after model criticism are presented below. *P*-values were determined using the package lmerTest (Kuznetsova et al., 2016); significant *p*-values are reported at $p < .05$.

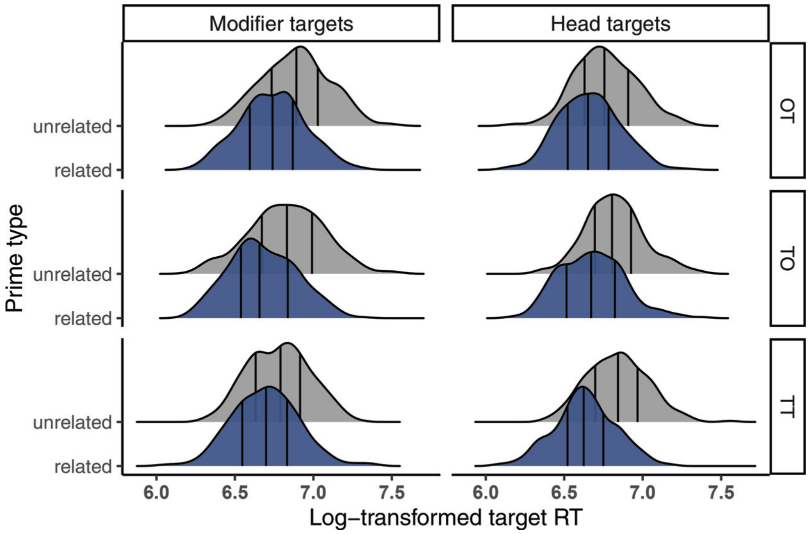
Results

The results are given in Figure 1 and in Table 3; priming effects are shown in Figure 2. The model for modifier targets (Experiment 1a) revealed a significant effect of prime type ($\beta = .130$, $p < .001$), with faster RTs to modifier constituents after related primes compared with unrelated primes. The post hoc contrasts revealed that all three conditions showed significant differences between related and unrelated prime types (OT: $\beta = –.138$, $p < .001$; TO: $\beta = –.166$, $p < .001$; TT: $\beta = –.086$, $p = .001$). In other words, significant priming effects were obtained for all compound types. The interaction between condition and prime type further showed that the difference in priming between OT and TO was not significant ($p = .389$), whereas the difference between the opaque conditions (OT and TO) and the TT condition was significant ($\beta = –.020$, $p = .027$), with greater priming effects for the opaque conditions relative to the TT condition.

The model for head targets (Experiment 1b) also showed a significant effect of prime type ($\beta = .153$, $p < .001$). The post hoc contrasts again revealed that all three conditions showed significant priming effects (OT: $\beta = –.114$, $p < .001$; TO: $\beta = –.141$, $p < .001$; TT: $\beta = –.203$, $p < .001$). As for the modifier targets, the interaction between condition and prime type showed that the difference in priming between OT and TO was not significant for head targets either ($p = .322$). The difference between the opaque conditions (OT and TO) and the TT condition was significant ($\beta = .025$, $p = .003$), with a greater priming effect for the TT condition relative to the opaque conditions.

Figure 1

Stacked Density Plots for Log-Transformed Prime RTs in Experiment 1a (Modifier Targets) and Experiment 1b (Head Targets) in the Different Conditions (OT, TO, TT)



Note. The lines correspond to the first, second, and third quartile. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent. See the online article for the color version of this figure.

Table 3

Mean Response Times (in ms; Standard Errors in Parentheses) to Targets Preceded by a Related or Unrelated Prime and the Resulting Priming Effects in Experiment 1a (Modifier Targets) and Experiment 1b (Head Targets) in the Different Conditions (OT, TO, TT)

	Modifier target			Head target		
Condition	Related prime	Unrelated prime	Priming effect	Related prime	Unrelated prime	Priming effect
OT	863 (10.60)	1,001 (13.82)	138 (17.42)	796 (9.55)	885 (10.94)	89 (14.52)
TO	813 (10.36)	950 (14.30)	137 (17.66)	809 (10.57)	931 (11.13)	122 (15.35)
TT	827 (10.67)	897 (10.44)	70 (14.93)	775 (8.97)	952 (11.69)	177 (14.74)

Note. For priming effects, the standard errors of the sampling distribution of differences are provided. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent.

The model for modifier targets also revealed a significant effect of target frequency ($\beta = -.020$, $p = .034$), showing that participants responded faster to high frequency modifier targets than to low frequent ones. The effect of target frequency in the model for head targets did not reach significance ($p = .494$). The opposite pattern was found for prime (i.e., compound) frequency, which was marginally significant in the model for head targets ($\beta = .0185$; $p = .082$), and not significant in the model for modifier targets ($p = .935$). Moreover, both models revealed significant effects for prime RT (modifier targets: $\beta = .052$, $p < .001$; head targets: $\beta = .057$, $p < .001$), indicating that participants responded slower to targets after having taken longer to respond to the prime. As expected, because RTs were measured from the start of the sound file, the effect of target duration was also significant in both models (modifier targets: $\beta = .036$, $p < .001$; head targets: $\beta = .053$, $p < .001$). Trial number and ISI were significant only with head targets (trial: $\beta = -.026$, $p < .001$; ISI: $\beta = .009$, $p = .012$), but not with modifier targets (trial: $p = .722$; ISI: $p = .133$).

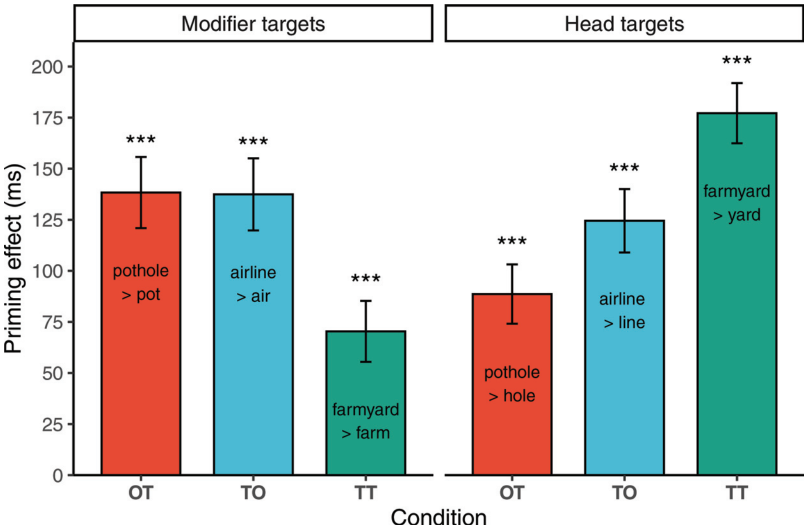
In sum, the main results of this experiment are that OT, TO, and TT compounds facilitate recognition of both their modifier and head constituents, regardless of their semantic transparency or opacity. These results replicate the results from some earlier priming studies (Fiorentino & Fund-Reznicek, 2009; Libben et al., 2003; Shoolman & Andrews, 2003), but do so in the auditory as opposed to the visual modality. Moreover, for both modifier and head targets, significant differences between the means of the partially opaque conditions (OT/TO) and the transparent (TT) condition were found. For modifier targets, the results showed a smaller priming effect for transparent compared with opaque compounds, while for head targets, the results showed a greater effect for transparent compounds. The difference between the two opaque conditions was not significant. This suggests that the opaque conditions pattern together, to the exclusion of the transparent condition, and that this holds for both modifier and head targets.

Experiment 2

Because Experiment 1 established significant priming effects for all compound types regardless of semantic transparency, the goal of

Figure 2

Priming Effects (in ms) in Experiment 1a (Modifier Targets) and Experiment 1b (Head Targets) in the Different Conditions (OT, TO, TT)



Note. Priming effects reflect the difference in response time (RT) to the target when it is preceded by a related versus an unrelated prime. Error bars represent ±1 standard error of the sampling distribution of differences. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent. *** $p < .001$. See the online article for the color version of this figure.

Experiment 2 was to further examine the differences between modifier and head constituents. Note that Experiment 1 was not designed to directly compare the effects for modifier and head constituents, as it employed a between-target design with different targets for the modifier/head manipulation (e.g., *farmyard* → *farm*/*yard*). If we were to compare effects for modifier versus head constituents in such a design, potential differences in RTs between the modifier and head targets could result from specific target properties. To eliminate this confound, Experiment 2 applies a within-target manipulation in which the same target is presented in multiple prime contexts, and hence, RTs to the same target across different prime conditions are compared. As a result, distributional differences among target words can be better controlled (Feldman, 2000; Milin, Smolka, & Feldman, 2018). Experiment 2 used the same conditions and critical stimuli as Experiment 1 but reversed the order of primes and targets such that the compound formed the target.

Method

Participants

Participants were 97 undergraduate students at the University of Pennsylvania, who reported to being native speakers of English. As for Experiment 1, a power calculation in G*Power (Faul et al., 2007) indicated that with 12 items per condition, a sample size of 15 was sufficient to detect a main effect of condition with an effect size f of at least .25 with 80% power. To account for the interaction with prime type (modifier/head/unrelated), we included twice as many participants per cell, which led to our goal of including at least 90 participants ($15 \times 3 \times 2$) in this experiment. Participants who took part in Experiment 1 were excluded from participation. Ethical approval for the study was provided by the Institutional Review Board at the University of Pennsylvania. Participants provided informed consent and received course credit as compensation for their participation.

Materials

The same partially opaque (TO or OT) and transparent (TT) compounds that were used in Experiment 1 were included in Experiment 2. We included 12 prime–target pairs per condition. In contrast to Experiment 1, targets were compounds, while primes were either the modifier constituent, the head constituent, or an unrelated word. Sample critical items are given in Table 4. See the online supplemental material for the full stimulus list.

The related primes were matched to unrelated primes on the basis of the average frequency of the modifier and head constituents. All unrelated primes were unrelated in meaning and phonology to the related primes and the compound targets. Different from Experiment 1, unrelated primes in Experiment 2 were monosyllabic words so that they would be as similar as possible to the related primes. Mean frequencies in the different conditions are summarized in Table 5. The same filler words and pseudowords as in Experiment 1 were included in Experiment 2.

Apparatus

The apparatus for this experiment was identical to that of Experiment 1.

Table 4

Conditions and Sample Critical Items in Experiment 2

	Prime type			
Condition	Modifier	Head	Unrelated	Target
OT	*pot*	*hole*	*roof*	*pothole*
TO	*air*	*line*	*piece*	*airline*
TT	*farm*	*yard*	*prince*	*farmyard*

Note. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent.

Procedure

Similar to Experiment 1, a continuous lexical-decision task was used. Experiment 2 consisted of three lists, with modifier, head, and unrelated primes to the same target rotated on different lists. The task had a random ISI between 800 ms and 1,000 ms. As in Experiment 1, the task consisted of four blocks with the possibility for a self-administered break after each block, and a practice phase of 14 items at the beginning of the experiment. The experiment lasted for 13 min on average. See the Procedure section for Experiment 1 for further details.

Analysis

The data were analyzed in a similar way as in Experiment 1. Four participants were excluded due to overall low accuracy across all stimuli ($<75\%$) and two participants were excluded because they indicated that they were not native speakers of English. Trials with incorrect responses to primes or targets were discarded, which led to an exclusion of 340 data points out of a total of 3,276 trials (10.38%). The RT data were log-transformed, and all targets with outlier RTs (<100 ms and $>2{,}000$ ms) were excluded, as well as the targets for which the prime had an outlier RT. This led to the exclusion of 72 data points. The RT data were log-transformed, and removal of outliers was done for 21 individual participants for who Shapiro-Wilk's tests for normality showed nonnormal distributions, which led to the exclusion of 44 observations. The same was done for 16 individual items, leading to the exclusion of 29 further observations.

As for Experiment 1, the effects on log-transformed RT were analyzed with linear mixed-effects models. Random intercepts for participants, targets, and primes were included, and fixed effects included an interaction between condition (OT/TO/TT) and prime type (modifier/head/unrelated), as well as group, ISI, target frequency, prime frequency, target duration, log prime RT, and trial. In addition to these fixed effects, which were also included in Experiment 1, the acoustic signal of each compound was visually and acoustically inspected to determine the onset of the head constituent (following Koester et al., 2009). This was added as the predictor onset head in the model.

As for Experiment 1, condition was coded with Helmert contrasts, such that the first contrast coded the difference between the partially opaque OT and TO conditions (coefficients: OT = –1, TO = 1, TT = 0), and the second contrast tested the difference between the transparent TT condition and the mean of both partially opaque conditions (both –1). Prime type was treatment coded with the unrelated prime condition as the reference level. Post hoc comparisons between the levels of prime type (modifier/

Table 5

Mean Frequencies Per Condition and Per Prime and Target Type in Experiment 2

	Prime type			
Condition	Modifier	Head	Unrelated	Target
OT	2.91 (0.53)	3.34 (0.35)	3.11 (0.44)	1.67 (0.48)
TO	3.10 (0.57)	3.10 (0.48)	3.18 (0.36)	1.74 (0.52)
TT	3.19 (0.48)	2.89 (0.61)	3.03 (0.43)	1.63 (0.50)

Note. Frequencies (Lg10CD) were extracted from the SubtLex-US database (Brysbaert et al., 2012). OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent.

head/unrelated) within each level of condition were performed with emmeans (Lenth et al., 2018). The continuous variables were centered. Model criticism was performed on the full model to identify overly influential outliers (Baayen & Milin, 2010), which removed 66 observations (or 2.37%).

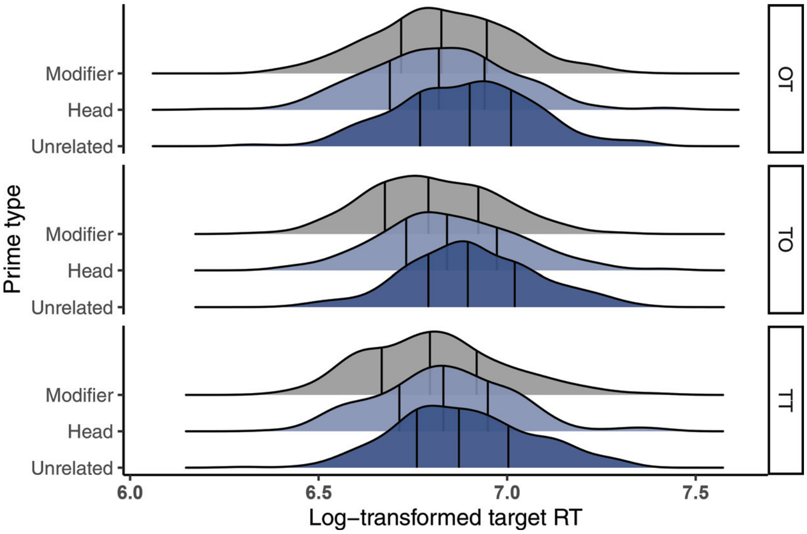
Results

The results are shown in Figure 3 and in Table 6. The numerical priming effects show that both modifier and head constituents facilitated the recognition of the compound in which they occur, regardless of the semantic transparency of that constituent. The model revealed a significant difference between RTs to targets after unrelated versus modifier primes ($\beta = -.088$, $p < .001$), and between unrelated and head primes ($\beta = -.055$, $p < .001$) across conditions. The post hoc contrasts showed significantly faster responses after modifier primes compared with unrelated primes in all three conditions (OT: $\beta = .071$, $p = .002$; TO: $\beta = .121$, $p < .001$; TT: $\beta = .073$, $p = .001$). After head primes, significantly faster responses compared with unrelated primes were found in the TO condition ($\beta = .063$, $p = .006$) and in the TT condition ($\beta = .055$, $p = .019$). Although the size of the priming effect after head primes in the OT condition (65 ms, see Figure 4) was numerically larger than the effects in the TO (52 ms) and TT (51 ms), it did not come out as significant in the model ($p = .052$) for reasons unclear to us.

Recall that this experiment was designed to examine whether differences exist between modifier and head priming effects on the recognition of the same target. The post hoc contrasts showed that RTs to targets after modifier and head primes did not differ with OT compounds ($p = .446$) and with TT compounds ($p = .639$). Crucially, however, the RTs after modifier primes did significantly differ from RTs after head primes in the TO condition ($\beta = .058$, $p = .012$), with faster responses after transparent modifier primes compared with opaque head primes. This suggests that the modifier/head distinction as posited for compounds plays at least some role in processing, with a greater priming effect after modifier primes in the TO condition that are transparently related to the compound, compared with opaque head primes. The results did not show a similar difference in priming effects between priming

Figure 3

Stacked Density Plots of the Log-Transformed Response Times in Experiment 2 to Targets Preceded by an Unrelated Word, the Modifier Constituent, or the Head Constituent in Experiment 2



Note. The lines correspond to the first, second, and third quartile. OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent. See the online article for the color version of this figure.

Table 6

Results Experiment 2: Mean (Standard Errors in Parentheses) Response Times (RTs; in ms) to Targets and Priming Effects

	Modifier prime		Head prime		
Condition	RT	Priming	RT	Priming	Unrelated prime RT
OT	940 (9.92)	58 (14.65)	933 (10.09)	65 (14.77)	998 (10.78)
TO	914 (9.17)	99 (13.59)	961 (10.48)	52 (14.51)	1,013 (10.03)
TT	922 (9.87)	72 (14.42)	943 (10.05)	51 (14.55)	994 (10.52)

Note. For priming effects, the standard errors of the sampling distribution of differences are provided.

by an opaque modifier and transparent head in OT compounds. Note also that if what mattered was the linear order in which modifiers (first constituents) and heads (second constituents) are presented, modifier constituents should have induced greater priming effects in all three compound conditions. However, a significantly greater effect for modifier compared with head constituents was found only for TO compounds.

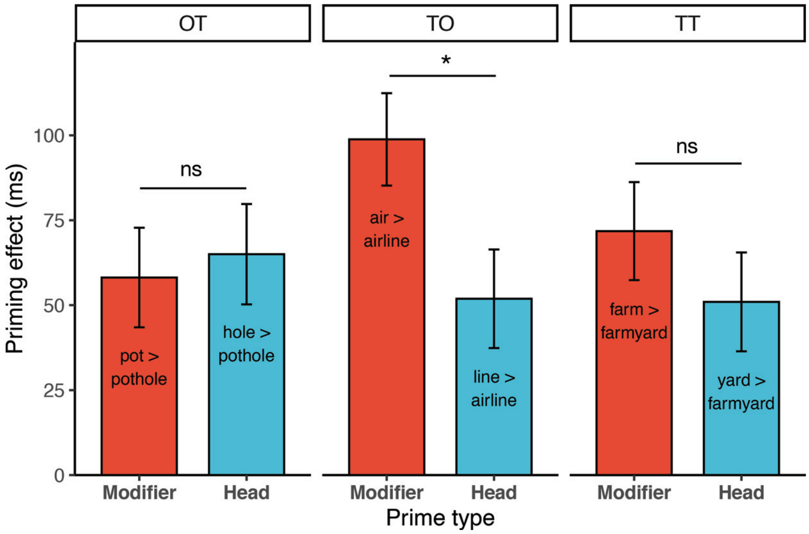
The interaction between condition and prime type revealed a marginally significant effect of condition (OT vs. TO) on modifier priming ($\beta = -.025$, $p = .080$), with a larger modifier priming effect in the TO condition compared with the OT condition. None of the further interactions were significant (modifier priming between opaque conditions and TT: $p = .334$; head priming between OT and TO conditions: $p = .563$; head priming between opaque conditions and TT: $p = .984$). It is important to keep in mind that this comparison is made between different compound targets.

Finally, the model revealed significant effects for prime RT ($\beta = .043$, $p < .001$), and onset head ($\beta = .046$, $p = .001$), a measure of the onset of the head constituent. A marginally significant effect was found for trial number ($\beta = -.011$, $p = .064$), and no significant effects were found for ISI ($p = .182$), prime frequency ($p = .591$), target frequency ($p = .144$), and target duration ($p = .964$).

In sum, Experiment 2 directly compared priming by modifier and head constituents and found a significant difference only in the TO condition, in which the heads were semantically opaque. This finding, at first sight, may suggest that the opaque heads in TO compounds induce an increased processing cost. The finding that unprimed RTs to compounds with transparent heads (OT: 998 ms; TT: 994 ms) were numerically shorter than RTs to compounds with opaque heads (TO: 1,013 ms) further suggests that compounds with opaque heads may be more difficult to process, in line with the finding that compounds with opaque heads take longer to recognize than compounds with transparent heads in visual word recognition (Libben et al., 2003). However, a different explanation for the current findings is that the difference between modifier and head priming in the OT compound condition is driven by the large effect

Figure 4

Priming Effects (in ms) for Targets Preceded by Modifier or Head Constituents in Experiment 2 in the Different Conditions (OT, TO, TT)



Note. Priming effects reflect the difference in response time (RT) to the target when it is preceded by a related versus an unrelated prime. Error bars represent ±1 standard error of the sampling distribution of differences. ns = not significant; OT = opaque–transparent; TO = transparent–opaque; TT = transparent–transparent. * $p < .05$. See the online article for the color version of this figure.

for modifier priming, not by a smaller effect for head priming. The interaction between condition and prime type indeed showed that the effect for modifier priming was larger in the TO condition compared with the OT condition (see Figure 4), whereas the effects of head priming did not differ between the OT and TO conditions and between the opaque and TT conditions.

Experiment 3 was designed to examine the difference between opaque and transparent heads in more detail. To do so, we compared the effects of priming by partially opaque (OT/TO) and transparent compounds on head recognition. In particular, Experiment 3 examined to what extent head constituents can be primed by OT and TT compounds, which both have transparent heads, and by TO and TT compounds, which differ in terms of the semantic transparency of the head.

Experiment 3

In Experiment 3, the partially opaque (OT/TO) compound primes that were used in Experiments 1 and 2 were matched by their head constituent to fully transparent (TT) compounds, such that, for instance, *pothole* (OT) was matched to *keyhole* (TT). Experiment 3 examined whether these compounds facilitate recognition of their head constituent, *hole* (relative to matched unrelated compounds). In the case of *pothole* and *keyhole*, both occurrences of *hole* contribute a semantically transparent meaning to the compound. Crucially, we also matched TO compounds like *airline* to TT compounds *fishline*. Here, the head *line* is transparently related to the full compound in the TT compound, but not in the TO compound. We tested whether head recognition is influenced by its semantic relationship to the full compound.

The design in Experiment 3 is similar to the design used in Smolka and Libben (2017) for German compounds. Smolka and Libben (2017) tested the effects of both modifier and head priming on compound recognition. In our experiment, we reversed the order of compounds and constituents, such that we compared priming effects on the same target in OT/TT and TO/TT compounds. In addition, we only examined the effects of compound priming on head constituent recognition, and not on modifier constituent recognition. The available opaque compounds in English restricted our options, and it was impossible to match all included OT and TO compounds to TT compounds based on their modifier constituents. Finally, we distinguished between OT and TO compounds, whereas Smolka and Libben (2016) included different types of opaque stimuli within the semantically opaque condition, with the transparency of the modifier and head constituents added as predictors in the model.

Method

Participants

Participants were 93 undergraduate students at the University of Pennsylvania. According to the power analysis reported for Experiment 1 and 2 (for details, see Experiment 1), this should give us enough power to detect an interaction between condition and Prime type. All participants reported to being native speakers of English and participants who took part in Experiments 1 and 2 were excluded from participation. Ethical approval for the study was provided by the Institutional Review Board at the University of Pennsylvania. Participants provided informed consent and received course credit as compensation for their participation.

Materials

As in Experiment 1, compounds formed the primes and head constituents formed the targets. A within-target comparison was used for the different prime types within each compound condition. The two partially opaque conditions (OT, TO) that were included in Experiment 1 and 2 were included here as well, with the same 12 critical items per condition. These items were matched to TT compounds that shared the same head constituent. We refer to the two conditions, which now consist of both partially opaque and fully transparent compounds, as XT (OT and TT) and TX (TO and TT). Sample critical items are given in Table 7; a full stimulus list can be found in the online supplemental materials.

The transparent compounds were part of the semantic relatedness norming study described for Experiment 1 and had high semantic relatedness scores to both of their constituents (see Table 8). A one-way ANOVA performed on the mean semantic relatedness scores for head constituents showed highly significant differences between conditions, $F(3, 44) = 89.23$, $p < .001$. Post hoc testing with Tukey's test showed that the semantic relatedness scores for the transparent heads in the XT and OT conditions itself did not significantly differ ($p = .646$), whereas the relatedness scores for the heads in the TX and TO conditions did significantly differ ($p < .001$). The different transparent conditions did not differ from each other ($p = .997$).

The transparent compounds were matched as much as possible on frequency to the opaque compounds (see Table 8). The unrelated compound primes that were included in Experiment 1 were used in this experiment as well. Finally, we included a total of 168 filler items. Since each participant in this experiment heard fewer critical items than in the previous experiments, we decreased the number of fillers compared with Experiments 1 and 2. Of the fillers, 60 were words: 30 monosyllabic and monomorphemic words, 15 compound words, and 15 derivationally complex words (e.g., *brightness*); and 108 were pseudowords. Half of the pseudowords were monosyllabic and half were disyllabic with stress on the first syllable, to resemble the stress in compound words.

Apparatus

The apparatus for this experiment was identical to that of Experiment 1.

Procedure

Similar to the previous experiments, a continuous lexical-decision task was used. Experiment 3 consisted of three lists, with opaque, transparent, and unrelated primes to the same target rotated

Table 7
Conditions and Sample Critical Items in Experiment 3

	Prime type			
Condition	Opaque	Transparent	Unrelated	Target
XT	*pothole*	*keyhole*	*swordplay*	*hole*
TX	*airline*	*fishline*	*earthquake*	*line*

Note. XT = opaque or transparent modifier, transparent head; TX = transparent modifier, opaque or transparent head.

Table 8
Stimuli Characteristics in Experiment 3

	Prime frequency				Semantic score	
Condition	Opaque	Transparent	Unrelated	Target frequency	Opaque	Transparent
XT	1.67 (0.48)	1.56 (0.71)	1.64 (0.48)	3.34 (0.35)	5.27 (0.85)	5.59 (0.48)
TX	1.74 (0.52)	1.36 (0.80)	1.56 (0.70)	3.10 (0.48)	1.91 (0.36)	5.53 (0.70)

Note. Frequencies (Lg10CD) were extracted from the SubtLex-US database (Brysbaert et al., 2012). Mean (standard deviations in parentheses) semantic relatedness scores are given for the head constituent in XT (OT/TT) and TX (TO/TT) compounds. Ratings were on a 7-point scale (1 = *completely unrelated in meaning*; 7 = *highly related in meaning*). XT = opaque or transparent modifier, transparent head; OT = opaque-transparent; TT = transparent-transparent; TX = transparent modifier, opaque or transparent head; TO = transparent-opaque.

on different lists. The task had a random ISI between 800 ms to 1,000 ms. The experiment consisted of three blocks with the possibility for a self-administered break after each block, and a practice phase of 14 items at the beginning of the experiment. The experiment lasted for about 9 minutes on average. See the Procedure section for Experiment 1 for further details.

Analysis

Three participants were excluded due to overall low accuracy across all stimuli (<75%), and one participant was excluded because they indicated they were not a native speaker of English. Trials with incorrect responses to primes or targets were discarded, which led to an exclusion of 261 observations out of a total of 2,136 trials (12.22%). The RT data were log-transformed, and all targets with outlier RTs (<100 ms and >2,000 ms) were excluded, as well as the targets for which the prime had an outlier RT, removing 56 data points. The RT data were log-transformed, and removal of outliers was done for 13 individual participants and five individual items for which Shapiro-Wilk's tests for normality showed nonnormal distributions, which led to the removal of 37 data points. In total, a-priori data trimming led to the exclusion of 93 observations, or 4.85%.

We analyzed effects on log-transformed RT with a linear mixed-effects model, including random intercepts for participants, targets, and primes. Fixed effects included a two-way interaction between condition (XT, TX) and prime type (opaque, transparent, and unrelated). Additional predictors were group, ISI, target frequency, prime frequency, target duration, log prime RT, and trial. Condition was coded using sum coding with coefficients –.5 for XT and .5 for TX. Prime type was treatment coded, with the reference level set to the opaque condition. Post hoc comparisons were performed with emmeans (Lenth et al., 2018). We compared the levels of prime type (unrelated/opaque/transparent) within each level of condition (XT/TX). The continuous variables were centered, and model criticism was performed on the full model, after which an additional 51 data points were excluded (2.86%). The model was refitted after model criticism, the results of which are presented in the following text.

Results

The results are shown in Figure 5, Figure 6, and Table 9. The model revealed a significant difference between opaque and unrelated primes (β = .119, $p < .001$), and no significant difference between opaque and transparent primes (p = .168) across conditions. Within the XT condition, the post hoc contrasts revealed significant priming effects after opaque primes (β = .161, $p < .001$) and after transparent primes (β = .153, $p < .001$), compared unrelated primes. The same held for the TX condition, in which again both opaque (β = .078, $p < .001$) and transparent (β = .109, $p < .001$) primes led to significant priming effects. The results, therefore, showed significant priming effects for all compound conditions: OT, TO, and TT compounds prime their head constituents.

The experiment was designed to compare the effects of priming by partially opaque (OT/TO) and transparent (TT) compounds on head recognition. The model revealed that the difference between RTs after opaque and transparent primes was not significant in the XT condition (p = 1.00). In other words, when comparing the effects of OT and TT compound primes on head recognition in the XT condition, we did not find a significant difference between OT compounds (*pothole* → *hole*) and TT compounds (*keyhole* → *hole*). Crucially, in this case, both compound primes were related in meaning to the target, and the results suggest that the opacity of the modifier constituent in the prime did not matter for the magnitude of facilitation of the head constituent on the target.

In contrast, in the TX condition, the difference between RTs after opaque and transparent primes was significant (β = .032, p = .048), with longer RTs after opaque primes compared with transparent primes. This translates to a smaller priming effect in the opaque prime condition, as shown in Figure 6. In other words, the model showed a difference in facilitation after TO (*airline* → *line*) and TT (*fishline* → *line*) compound primes, for which the head constituent that formed the target was semantically opaque in TO compounds but not in TT compounds. We, thus, found greater facilitation when the head of the compound was semantically transparent than when it was semantically opaque.

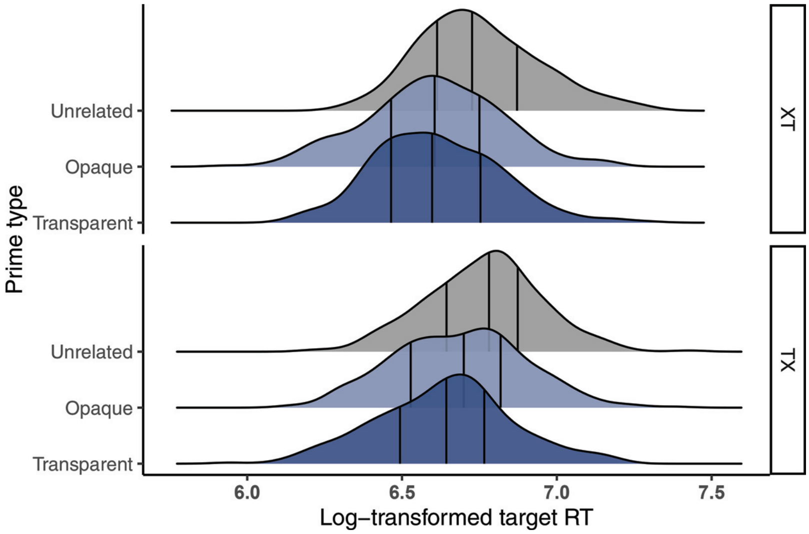
The interaction between condition and prime type showed that the facilitation in the XT and TX conditions was significantly different after opaque primes, relative to unrelated primes (β = –.0829, $p < .001$), and that the difference in RTs to targets after opaque and transparent primes was different between the XT and TX conditions (β = –.039, p = .016). However, it is important to keep in mind that this comparison is made between different targets. Finally, the model showed significant effects for prime RT (β = .039, $p < .001$), trial (β = –.026, $p < .001$), target duration (β = .051, p = .002), prime frequency (β = .029, $p < .001$). No significant effects were found for ISI (p = .065) and target frequency (p = .656).

General Discussion

We presented the results of a series of primed lexical decision experiments that examined the processing of semantically transparent

Figure 5

Stacked Density Plots for Log-Transformed Prime RTs in Experiment 3

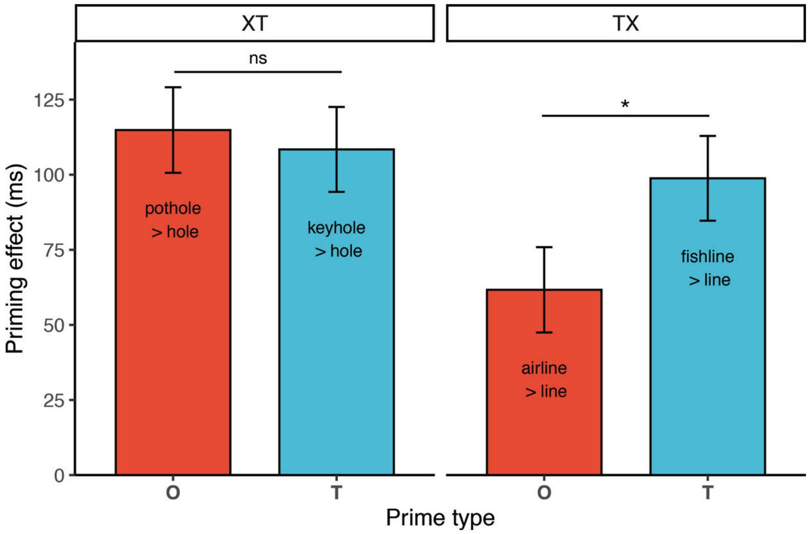


Note. Plots are for the XT and TX conditions in which targets (e.g., *hole, line*) were preceded by partially opaque (XT: *pothole*; TX: *airline*), transparent (XT: *keyhole*; TX: *fishline*), or unrelated primes. The lines correspond to the first, second, and third quartile. See the online article for the color version of this figure.

and partially opaque English compounds in the auditory modality. Our first aim was to determine whether prior activation of a morphological constituent in a compound affects the processing of that constituent in spoken word recognition, and to what extent these effects are affected by the semantic transparency of a compound. Our second aim was to test whether semantic transparency effects are different for heads and modifiers. We discuss our results with respect to these research questions in the following text.

Figure 6

Priming Effects (in ms) in Experiment 3



Note. Priming effects are for the XT and TX conditions in which targets (e.g., *hole*, *line*) were preceded by partially opaque (XT: *pothole*, TX: *airline*) or transparent (XT: *keyhole*, TX: *fishline*) compounds. Error bars represent ±1 standard error of the sampling distribution of differences. ns = not significant. * $p < .05$. See the online article for the color version of this figure.

Table 9

Results Experiment 3: Mean Response Times (in ms) to Targets and Priming Effects

	Opaque		Transparent		Unrelated
Condition	RT	Priming	RT	Priming	RT
XT	752 (9.64)	115 (14.26)	759 (9.46)	108 (14.13)	867 (10.50)
TX	819 (10.20)	62 (14.21)	782 (10.07)	99 (14.12)	880 (9.90)

Note. For response times, standard errors of the mean are given in parentheses; for priming effects, the standard errors of the sampling distribution of differences are provided.

Semantic Transparency

The three experiments in this article showed priming effects in all conditions, both for constituent targets (Experiments 1 and 3) and for compound targets (Experiments 2, although the effect after head primes in the OT condition was only marginally significant here). The results for Experiment 1 showed that the presentation of an OT, TO, or TT compound facilitates recognition of both its modifier and head constituent, regardless of its semantic transparency or opacity. Experiment 2 showed that the reverse holds as well: the presentation of a modifier or head constituent primes the recognition of a compound that contains that constituent, also in opaque compounds. This holds for opaque modifiers in OT compounds and for opaque heads in TO compounds. These results provide evidence that compounds are decomposed into their constituent words in the auditory modality.

These findings are in line with the results in visual nonmasked constituent priming studies on compounds (e.g., Ji et al., 2011; Libben et al., 2003; Smolka & Libben, 2017), and show that compounds prime and are primed by both modifier and head constituents in the auditory modality as well. The latter point is consistent with the results in an auditory study by Koester et al. (2004), who manipulated the syntactic gender agreement between a determiner and the initial compound constituent (the modifier constituent), and between a determiner and the last constituent (head) during auditory processing using event-related brain potentials. Gender-incongruent constituents elicited a left-anterior negativity for both constituents and with both semantically transparent (TT) and opaque (OO) compounds. The results showed that syntactic gender information of modifier constituents is available, which was taken as evidence that both transparent and opaque compounds are decomposed during auditory word processing.

Modifiers Versus Heads

Our second aim was to examine whether the effects of semantic transparency are different for heads and modifiers, asking whether OT (opaque modifier, transparent head) and TO (transparent modifier, opaque head) compounds are processed differently.

Experiment 1 provided an initial indication of this kind of effect, as there were significant differences between the mean of the partially opaque conditions (OT/TO) and the transparent (TT) condition both with modifier targets and with head targets. For modifier targets, the results showed a *smaller* priming effect for transparent compared with opaque compounds, while the results showed a *greater* effect for head targets. The finding of greater facilitation after TT compounds (transparent head) compared with TO compounds (opaque head) when priming the head constituent is consistent with the results in Experiment 3, as will be discussed in more detail in the next section. At this point, however, it is unclear how to explain the smaller priming effects for transparent modifiers in TT compounds, compared with the modifiers in OT and TO compounds in Experiment 1. A question for future work is whether this is artifact of the between-target comparison in this experiment, or whether the finding can be replicated.

Experiment 2 offered a within-target comparison for modifier versus head effects. Using the same compound targets within each condition (OT, TO, TT), we compared RTs to the same target preceded by modifier and head primes. The results showed that RTs to targets after modifier and head primes did not differ for OT and TT compounds, while they did differ in the TO condition, with faster responses after transparent modifier primes compared with opaque head primes. While this finding seems to be in line with an approach according to which compounds with opaque heads are more difficult to process than compounds with transparent heads (see for similar results Libben et al., 2003), it is likely that the difference between head and modifier priming was actually driven by the larger priming effect for modifier priming with TO compounds rather than a smaller priming effect for head priming.

Note that if the distance between primes and targets (i.e., whether an "intervening constituent" occurred between the repeated constituents) was alone responsible for differences between modifiers and targets, modifier constituents should have induced more priming than head constituents in all compound conditions in Experiment 2, and heads should have induced more priming than modifiers in Experiment 1. This is not what we found.

Transparent Versus Opaque Heads

As discussed in the preceding text, from the results of Experiment 2, it remains unclear whether opaque heads induce an increased processing cost relative to transparent modifiers within the same compound. To examine the processing of transparent and opaque *heads* in more detail, Experiment 3 compared the effects of priming by partially opaque (OT/TO) or matched transparent compounds (with the same head) on head recognition. The results showed no significant difference between OT compounds (*pothole* → *hole*) and TT compounds (*keyhole* → *hole*). In this case, both compound primes were related in meaning to the head target, as the compounds both had transparent heads. However, a significant difference was found between TO (*airline* → *line*) and TT (*fishline* → *line*) compound primes, in which the head constituent that formed the target is semantically opaque in TO compounds but not in TT compounds. A larger priming effect was found when the head of the compound was semantically transparent than when it was semantically opaque.

Considering the robust priming effects for constituents and compounds throughout Experiments 1–3 (with the exception of head priming in the OT condition in Experiment 2), it is unlikely that the opaque *line* constituent in *airline* is not represented as a separate constituent. Instead of these effects being driven by a representational difference between transparent and opaque heads (i.e., decomposed or not), it is likely that the smaller priming effect for *airline* (TO) → *line* compared with *fishline* (TT) → *line* is driven by a difference in *processing* between opaque and transparent heads.

Within a decompositional framework (e.g., Fruchter & Marantz, 2015; Taft, 2004), this could be implemented as follows. In an initial phase, all constituents are activated separately (i.e., decomposition). This happens regardless of semantic transparency. In a second stage (i.e., look-up), the lexical entries for the embedded activated constituents are accessed. In a final stage (i.e., recombination), the meanings of the constituents are combined to obtain the meaning of the compound. In this final stage of *semantic composition*, that is, the construction of complex meanings from the semantic/conceptual representations of the individual parts of morphologically complex words (Fruchter & Marantz, 2015; Ji et al., 2011), effects of semantic transparency may be manifested. At this stage, an increased processing cost would be found when the meaning of the opaque constituent conflicts with the actual meaning of the compound, as proposed by Ji et al. (2011) (see also Gagné & Spalding, 2004, 2006, 2009; Spalding & Gagné, 2014). Ji et al. (2011) suggested that this processing cost results from a conflict between the "constructed meaning" and the "conventional meaning" that needs to be resolved in order for the system to settle on one meaning. As meaning composition does not succeed in establishing the intended meaning for opaque compounds, the constructed meaning would need to be suppressed (i.e., inhibited) in favor of the stored, conventional meaning, leading to a reduction in priming effects (see also El-Bialy et al., 2013).

Alternative explanations, which do not rely on the concept of inhibition, are possible as well. It could be that the constituent's meaning is not inhibited per se, but that compounds with opaque constituents are more difficult to process than fully transparent ones because of the competition between the constituent's meaning and the whole-word meaning. This competition would then result in an added processing cost as reflected by the smaller priming effects in a priming experiment. A final possible explanation is not in terms of a processing cost for opaque heads, but rather in terms of an activation boost for transparent heads. Under this approach, all compounds show morphological priming, and in addition, semantically transparent heads also show semantic priming.

Further research is needed to determine whether semantic opacity of the modifier affects processing in the same way as semantic opacity of the head. If this is not the case for modifier constituents, this would suggest that the head has a special processing status in the semantic integration of compound constituents during the recombination stage, though perhaps not in decomposition per se. The fact that the meaning of a compound is generally determined by the meaning of its head, with the modifier merely limiting the meaning of the head, could explain the special status of heads in the semantic integration.[4] Although the results in Experiment 1 (in which no differences were found between the facilitation by OT and TO compounds on modifier recognition) and Experiment 2 (in which no difference was found between modifier and head priming in OT compounds) suggest that opaque modifiers may not affect processing to the same extent as opaque heads, a version of Experiment 3 with modifiers as targets is needed to rule this out. Such an experiment would compare priming by OT and matched TT compounds with the same modifier constituents as target; for instance, comparing *eggplant* (OT) → *egg* to *eggshell* (TT) → *egg*.[5] Notably, our materials did not allow for this comparison to be made, as such matched transparent compounds do not exist for enough OT compounds in the stimuli we have been able to assemble. While English does not provide the resources for such an experiment, it would be possible to undertake a study of this type in languages like German or Dutch, in which compounding is much more prevalent.[6]

Concluding Remarks

In a series of primed lexical decision experiments with English compound words, we examined the effects of semantic transparency on modifier and head constituents in the auditory modality. The main finding are the significant priming effects for both modifiers and heads, regardless of semantic transparency. The finding of morphological priming effects for compounds that are semantically opaque suggests that the individual constituents that make up a compound are accessed in opaque compounds as well. In addition, the findings suggest that opaque heads may induce an additional processing cost compared with transparent heads. This could arise from the need to suppress the head's meaning in favor of the stored meaning of the whole-word compound. It is also possible that the constituent's meaning is not suppressed or inhibited per se, but that the competition between the head's meaning and the whole-word meaning results in added processing that is reflected in priming. The results further illustrate the importance of distinguishing between OT and TO compounds, as opposed to employing a single 'opaque' condition in which TO and OT (and perhaps OO) compounds are collapsed. Our studies reveal differences between TO and OT compounds that would not be expected if semantic transparency were simply a property of a whole word (cf. Libben et al., 2003). An added factor is the demonstration that these differences derive from the status of the constituent in the compound (head/modifier), as distinct from the position of the element in the compound (first/second).

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[4] That is, with an opaque modifier like *pot* in *pothole*, the transparent meaning of *pot* is not part of the meaning of the compound. At the same time, no other semantic operation needs to be done to *pot* in order to produce the relevant meaning. Rather, the constituent *pot* indicates what kind of *hole* is being specified. *Pot* itself does not have a contextually determined meaning beyond this. The head, on the other hand, plays a much more significant role in the meaning of the whole word. A *pothole* is a kind of *hole*, but an *airline* is not a type of *line*. Thus, in addition to a potential suppression of the transparent meaning of *line*, the correct meaning ("commercial enterprise involved in transportation") has to be retrieved. A concept strongly related to the special status of heads is that of hyponymy (i.e., the semantic relation of category membership: e.g. a *pothole* is a *hole*), for which Gagné et al. (2020) showed that it is a critical component of the semantic transparency of constituents and compounds as a whole.

[5] See Smolka and Libben (2017) for a variant like this in the visual modality with German compounds.

[6] However, due to the incremental nature of the auditory modality, a different explanation for weaker transparency effects on modifiers is possible as well. A consequence of fact that the constituents are perceived serially in spoken-word processing is that the transparent/opaque distinction emerges in the course of processing, rather than being available from the beginning. For example, it is only after *berry* is processed that it is clear that *straw* has an opaque interpretation (and not a transparent one as in *straw hat*).

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