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Retrieving stem meanings in opaque words during auditory lexical processing

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ABSTRACT
Recent constituent priming experiments show that Dutch and German prefixed verbs prime their stem, regardless of semantic transparency (e.g. Smolka et al. [(2014). 'Verstehen' ('understand') primes 'stehen' ('stand'): Morphological structure overrides semantic compositionality in the lexical representation of German complex verbs. *Journal of Memory and Language*, *72*, 16–36. https://doi.org/10.1016/j.jml.2013.12.002]). We examine whether the processing of opaque verbs (e.g. *herhalen* "repeat") involves the retrieval of only the whole-word meaning, or whether the lexical-semantic meaning of the stem (*halen* as "take/get") is retrieved as well. We report the results of an auditory semantic priming experiment with Dutch prefixed verbs, testing whether the recognition of a semantic associate to the stem (*BRENGEN* "bring") is facilitated by the presentation of an opaque prefixed verb. In contrast to prior visual studies, significant facilitation after semantically opaque primes is found, which suggests that the lexical-semantic meaning of stems in opaque words is retrieved. We examine the implications that these findings have for auditory word recognition, and for the way in which different types of meanings are represented and processed.

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Semantic priming; lexical-semantics; semantic opacity; Dutch prefixed verbs; morphemes; auditory word recognition

1. Introduction

How words are represented and processed is a central topic in psycholinguistics and the study of the mental lexicon. A particular focus in this area of research is on words that appear to be morphologically complex (i.e. which look like they contain morphemes that occur elsewhere in the language) and which raise important questions about both representation and processing. In ways that are elaborated on in a number of different theoretical models, the most basic questions that are posed by such words concern whether they are represented as wholes, or decomposed into morphemes. A difficulty in identifying the role (if any) of specifically *morphological* representations is distinguishing among the many types of relatedness that may exist between words. Words that are morphologically related are often related in meaning and in form (phonology, orthography) as well (see Embick et al., in press; Zwitserlood, 2018, for discussion). Thus, putative effects of morphological relatedness for such words, as detected in priming or other paradigms, might instead reflect semantic and/or formal relatedness, and not shared morphological representation per se.

Prefixed verbs in Dutch and German have proven a fertile testing ground for distinguishing among the different types of relatedness (Creemers et al., 2020; De Grauwe et al., 2019; Smolka et al., 2009, 2014, 2015, 2019). The verbal systems of these languages contain a large number of verb stems that appear with a small set of prefixed elements. These prefixed verbs may be semantically *transparent*, that is, directly related in meaning to the meaning that the stem has on its own; or semantically *opaque*, with a meaning unrelated to the stem's. For instance, *afhalen* "take away/out" and *herhalen* "repeat" appear to share the stem *halen* "take/get", but only the former has a meaning related to the meaning of this stem. Some prefixed verbs have both transparent and opaque meanings, like *uitroeien*, literally "out-row", which can mean to "row out; finish by rowing" (transparent) or to "exterminate" (opaque).

The distinction between transparent and opaque prefixed verbs connects with an important argument in many different theoretical frameworks in linguistics, which holds that words that are irregular in terms of their form (irregular allomorphy) or meaning (semantic opacity) are represented differently from words with

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transparent forms and meanings (see e.g. Aronoff, 1976; Carstairs-McCarthy, 1992; Embick, 2015, for relevant discussion). A representational difference that is commonly appealed to, and one that plays a role in many contemporary approaches to the mental lexicon, is based on the idea that irregular words are stored as "unanalysable wholes", despite the appearance of internal complexity that they might have.

While the notion of being stored as a whole is itself one that could be examined further (cf. Embick et al., in press), it is significant that this type of approach cannot be straightforwardly extended to many Dutch prefixed verbs, as discussed in Creemers et al. (2020). Dutch (and German) prefixed verbs are of two types. One type has *inseparable* prefixes like *ver-*, *be-*, and *her-* which never occur apart from the stem. The other type has *separable* prefixes like *door*, *aan*, and *af*. Separable prefixes occur with the stem in many syntactic environments, but are separated from it and remain in clause-final position when the verb is found in the clause-initial position associated with the "verb second" phenomenon that is characteristic of many Germanic languages (cf. Den Besten, 1983; Schreuder, 1990). For instance, the separable prefix *aan* is separated from the stem *kijken* in a sentence context like *Zij* ***kijken*** *hem* ***aan*** "They look him in the eyes", but the inseparable prefix *be-* occurs with the stem in a similar sentence context: *Zij* ***bekijken*** *hem* "They look at him". Opaque meanings are found with verbs with both inseparable and separable prefixes. For example, the opaque verb *herhalen* "repeat" mentioned above occurs with the inseparable prefix *her-*, while an opaque verb like *opschieten* "hurry" (with the stem *schieten* "shoot") occurs with a separable prefix *op*, that is separated from the stem in a sentence context like *Zij* ***schieten*** *'s ochtends nooit* ***op*** "They never hurry in the mornings". Crucially, the syntactic separability of the prefix precludes a representation in which a word like *opschieten* "hurry" is a single, unanalysable word, and indicates that at least these verbs are internally complex.

Instead, the question that is at issue in prior work on the morphological structure of prefixed verbs has concerned *identity*: in particular, whether the stem seen in opaque verbs is the same as the unprefixed stem; or, for that matter, as the stem in a transparent prefixed verb. It could be the case, for example, that a prefixed verb like *herhalen* is internally complex, consisting of *her-* and *halen*, but with this *halen* being accidentally homophonous with *halen* "take/get" that occurs on its own and in transparent prefixed forms. Since accidental homophony appears to be present in the vocabulary of all languages, and (by definition) is found when the same phonological form is found with unconnected meanings, the possibility that opaque prefixed verbs are represented with stems homophonous to those found in transparent forms has to be considered.

A benefit of comparing stem-priming effects in transparent and opaque prefixed verbs is that the two verb types provide a way of distinguishing the effects of the different kinds of relatedness between words. Considering transparent and opaque primes in turn makes this point clear. The line of reasoning that has emerged in prior work on this topic is as follows. If transparent prefixed verbs facilitate recognition of their stem, the effect could in principle be attributed to several different types of relatedness (individually or in combination), since transparent prefixed verbs have considerable semantic and phonological overlap with their stems, in addition to any hypothesised morphological relationship (i.e. a shared stem). With opaque prefixed verbs, however, the prime word does not have a lexical meaning that is related to that of the stem. Taken at face value, then– and this is a point that we will discuss more in our General Discussion– facilitation effects for stems with opaque primes would not be attributed to overlap between the prime's meaning and that of the target. To the extent that formal relatedness is ruled out through the use of additional orthographic or phonological controls, facilitation of stems by opaque prefixed targets could straightforwardly be interpreted as being driven by a morphological representation; that is, a shared stem.

In this vein, an active literature that employs morphological constituent priming experiments has consistently shown that Dutch and German prefixed verbs prime their stem in overt visual, cross-modal, and auditory paradigms, regardless of semantic transparency (Creemers et al., 2020; De Grauwe et al., 2019; Smolka et al., 2009, 2014, 2015, 2019). In these studies, significant stem priming effects are found for semantically transparent (e.g. *afhalen* "take away/out" → *halen* "take/get") as well as semantically opaque (*herhalen* "repeat" → *halen* "take/get") prefixed verbs. These findings suggest that even opaque prefixed verbs are decomposed into a prefix and a stem, and that this stem is the same one that is seen in unprefixed (and transparent prefixed) occurrences of that verb. Using the examples above, this would mean that a word like *herhalen* "repeat" is represented and processed in a way that involves the stem *halen* "take/get", even though the two words are not related in meaning.

As suggestive as the conclusions emerging from this work are on their own, this line of investigation leaves a number of further questions about opaque forms unanswered. The particular one that we address in this paper concerns how the opaque meaning of a prefixed verb relates to the lexical semantic meaning of the stem.

Specifically, we examine whether or not the lexical-semantic meaning of the stem is retrieved in both transparent and opaque prefixed verbs. Using the example above, this is the question of whether the meaning of *halen* as "take/get" is retrieved when the prefixed verb *herhalen* "repeat" is processed. To do this, we make use of a semantic priming paradigm[1] that examines whether a semantic associate of the stem, such as *BRENGEN* "bring" to the stem *halen* "take/get", is primed by the presentation of an opaque prefixed verb.[2]

In principle, there are two possible ways in which semantically opaque prefixed verbs could be processed, which relate indirectly to theoretical perspectives that are more word-based versus morpheme-based, respectively. The first possibility (*Possibility 1*) is that when such words are processed, only the opaque meaning is retrieved. On this view, processing such words involves retrieving the "whole word" (i.e. opaque) meaning, in a way that excludes retrieval of the stem's lexical-semantic meaning. The second possibility (*Possibility 2*) is that when such words are processed, the meaning of the stem is activated as well. This might involve retrieval of the stem meaning either as an automatic consequence of activating that morpheme, or due to a processing strategy. In either case, the idea is that the stem meaning would be overridden by the contextually-determined (i.e. prefix-determined) opaque meaning. While strongly related to the literature on stem priming, instead of asking whether opaque forms are processed and represented with a stem that is the same as the one that occurs without a prefix, here we ask whether the processing of such verbs involves the automatic retrieval of the stem's lexical semantics, in addition to retrieving a meaning for the complex word.

1.1. Semantic stem priming with opaque words

Compared to morphological constituent priming studies, relatively few studies have examined the *semantic* (or associative) priming of morphemes in affixed words. In a visual semantic priming study with German and Dutch prefixed verbs, Zwitserlood et al. (1996) reported significant priming effects for the stem's meaning in semantically transparent verbs (*mitbringen* "bring" → *HOLEN* "get, pick up"), while no effects were found for semantically opaque prefixed verbs (*umbringen* "kill" → *HOLEN* "get, pick up"). Similar results were reported for a visual semantic priming experiment with transparent and opaque Dutch separable prefixed verbs, which instead used associates as primes and prefixed verbs as targets (De Grauwe et al., 2019, Experiment 3). In this study, significant priming effects were again reported for transparent verbs (*PEN* "pen" → *opschrijven* "write down", with *schrijven* "write"), but not for semantically opaque verbs (*SMULLEN* "to feast on" → *uitvreten* "to be up to", with *vreten* "devour").

Two cross-modal semantic priming studies showed similar results. Zwitserlood et al. (2005, Experiment 2) employed a cross-modal semantic priming paradigm in which spoken sentences (e.g. "He shouted all sorts of mean things when talking to her") served as primes to visual target words (e.g. transparent *uitschelden* "verbally abuse" or opaque *kwijtschelden* "remit payment"). The results suggest that Dutch opaque prefixed verbs cannot be semantically primed through the meaning of a transparent complex counterpart sharing the same morphological stem, whereas significant facilitation was found for semantically transparent targets and targets that were ambiguous between a transparent and opaque meaning (e.g. *uitroeien* "to exterminate" or "to finish by rowing"). Finally, in Smolka (2019, Experiment 2), neither semantically transparent (*anhören* "listen to"), nor semantically opaque (*aufhören* "stop") German prefixed verbs facilitated the recognition of semantic associates to the stem (*MUSIK* "music"). Smolka (2019) used auditorily presented prefixed verbs as primes, and semantic associates as visual targets.

While these studies reported that stems in semantically opaque complex forms are not primed by a semantic associate (or vice versa), and thus suggest that the meaning of the stem is not retrieved in such forms (*Possibility 1* above), it is important to consider several factors that might have contributed to the absence of facilitation. First, the two relevant conditions in Zwitserlood et al. (1996) occur in different experiments and with different Stimulus Onset Asynchronies (SOAs): 40 ms and 100 ms for the opaque verbs, and 300 ms for the transparent verbs. This complicates a direct comparison of these conditions. An important literature on visual morphological processing has highlighted the role of SOAs on semantic influences in morphological processing (e.g. Feldman et al., 2004; Rastle et al., 2000); thus, differences between the transparent and opaque conditions could be driven by differences in their respective SOAs. This is indeed what the authors suggest, since a different condition (e.g. *umbringen* "kill" → *MORD* "murder") also did not lead to significant priming effects in the shorter SOA experiment, while this condition did show significant priming in experiments with longer SOAs. Second, the designs in De Grauwe et al. (2019) and Zwitserlood et al. (2005) used between-target designs. The different priming patterns could thus, in principle, be due to differences between the individual targets in the different conditions. The comparison between differences (i.e. priming effects relative to an unrelated condition) rather than between target latencies, however, likely diminishes potential confounds by target properties. Finally, the null effect for semantically transparent verbs in Smolka (2019) is surprising, and begs the question of whether the particular cross-modal priming paradigm employed in that study is capable of detecting semantic priming effects at all. The lack of a stem condition (e.g. *hören* "hear" →*MUSIK* "music") makes it impossible to evaluate this for these particular results (for discussion see Smolka, 2019, p. 314).

In contrast to the results discussed above, Schreuder et al. (2003, Experiment 2) reported priming effects for the meaning of the stems in semantically opaque forms in a visual semantic priming task. Primes were Dutch low-frequency semantically opaque words like *branding* "surf, the rolling and splashing of the waves", which contains the high-frequency stem *brand* "fire, to burn" and the high-frequency nominalising suffix *-ing*. Targets referred either to the meaning of the stem of the prime (*VUUR* "fire"), or to the meaning of the full-form (*ZEE* "sea"). Significant facilitation for the stem-related condition was reported only with a SOA of 500 ms (prime display: 400 ms), but not with a SOA of 150 ms (prime display: 50 ms). In contrast, a significant effect for the full-form-related condition was found only at a 150 ms SOA, but not at a 500 ms SOA. The authors proposed that the first meaning to become available is the opaque full-form reading, and that the meaning of the stem is retrieved only later in time.

In summary, there are conflicting results concerning the retrieval of a stem's meaning in opaque morphologically complex words. The majority of studies that examined semantic priming of stems in affixed words have reported a lack of semantic priming effects with semantically opaque primes, suggesting that the meaning of the embedded stem is not retrieved. However, these studies are relatively few in number, and the conclusions should be treated cautiously for the reasons outlined above. It is also worth noting that the prevailing view on prefixed verbs differs from that found in the literature on the processing of opaque compounds (e.g. *strawberry* or *lawsuit*), where parallel questions can be asked. In work in that area, a prominent view holds that the lexical-semantic meanings of a compound's constituents are always accessed, also in opaque compounds (e.g. Ji et al., 2011; Spalding & Gagné, 2014). If it is indeed the case that the language system always attempts to compute a meaning based on a word's internal morphemes (e.g. Gagné & Spalding, 2004, 2006, 2009), semantic priming effects for the meaning of the stem in prefixed verbs would be predicted to occur as well. However, although compounds and prefixed words can both be transparent and opaque, the two types of complex words differ in other important ways. One notable difference is the word class of their constituents: compounds typically consist of lexical constituents, while prefixed words consist of a lexical stem as well as a prefix, which is often an adverb or preposition or a bound morpheme that does not necessarily possess a meaning by itself. These differences could in principle result in the activation of an opaque compound's constituent meaning but not of the stem meaning in a prefixed verb.

1.2. The present study

We designed an auditory primed continuous lexical decision experiment that uses semantic priming as a window into the question of whether the meaning of opaque words is activated exclusively, without retrieving the stem meaning (*Possibility 1*), or whether activation of a morpheme automatically involves the retrieval of its lexical-semantics, even in opaque words (*Possibility 2*). Specifically, the experiment explores whether the typical meaning of a stem such as *halen* as "take/get" is activated when one hears the Dutch opaque prefixed verb *herhalen* "repeat". Matched transparent prefixed primes like *afhalen* "take away/out" provide a further point of comparison. Targets are semantic associates of the prefixed verb primes. If the meaning associated with the stem is activated in a semantically opaque prefixed verb, we expect to find semantic priming effects for the stems in opaque verbs, relative to a control condition. If, however, the typical meaning of the stem of opaque prefixed verbs is not activated, we expect no semantic priming effects for the stems in opaque primes.

Prefixed verbs are particularly well-suited for probing the possible activation of the stem's meaning in opaque forms, due to the incremental nature of auditorily presented words. The prefix that induces the special interpretation for a particular stem is encountered first in the speech stream; in particular, before the stem is encountered. This means that it could be possible for the processing system to retrieve only the opaque meaning as the stem is processed, since the element that is responsible for the stem not contributing to a transparent meaning is encountered first in the auditory signal. That is, in processing the opaque word *herhalen*, the prefix *her-* is processed first. Therefore, it is in principle possible for the processing system to go directly to the opaque meaning for the whole word, without activating the stem meaning for *halen* (in the case of this word, the prefix *her-* also occurs in transparent words). By way of contrast, it is possible that with the temporal unfolding of suffixed words like *department*, retrieval of the stem meaning of *depart* occurs because this substring temporally *precedes* the part of the speech signal that produces the special interpretation (i.e. the suffix *-ment*). We return to this point– and the general question of how word embedding effects can be distinguished from activation of meanings in the sense targeted by *Possibilities 1* and *2*– in the General Discussion.

Different from previous studies, which used a purely visual or cross-modal (with visual targets) paradigm, we used an intra-modal auditory priming paradigm in which both primes and targets are presented auditorily. There are good reasons to believe that the processing of lexical representations from written words may differ in important ways from the processing of spoken words (cf. Marslen-Wilson et al., 1994). The two modalities, for instance, have a vastly different temporal structure. The auditory speech signal unfolds continuously in time, such that (as noted above) the listener does not have access to the prefix and stem at the same time (e.g. Wurm, 2000). In contrast, the letters that make up a visually presented word are simultaneously presented, such that prefixes and stems may be processed at the same time. These temporal differences may manifest themselves in significant ways in lexical access in general (e.g. Balling & Baayen, 2008, 2012; Marslen-Wilson, 1984) and in morphological processing in particular (for discussion, see Wilder et al., 2019).

Auditory presentation also has some direct effects on semantic priming that are of note (for discussion, see Hutchison, 2003). First, differences in the magnitude of semantic priming effects have been reported between visual and auditory paradigms, with much larger effects found in the latter. Second, the particular type of semantic (or associative) relation between primes and targets has been shown to matter greatly in the visual modality, while semantic priming has been shown to occur for all types of semantic relations in the auditory modality.

We have taken further steps to enhance the likelihood of finding semantic priming, as various previous semantic priming studies reported difficulties in detecting effects with verbs. Gomes et al. (1997, Experiment 1), for instance, examined semantic priming effects of visually and auditorily presented noun-noun (*dog* → *cat*) and noun-verb (*dog* → *bark*) stimulus pairs. The results showed faster response times to nouns than verbs, and larger priming effects for auditory than for visual targets (but see Rösler et al., 2001, who showed comparable priming effects for German noun-noun and verb-verb pairs in the visual modality). Semantic priming effects with prefixed verbs seem particularly hard to detect (Smolka et al., 2014; Zwitserlood et al., 1996). Using prefixed verbs as primes to verb targets (e.g. *zuschnüren* "tie" → *binden* "bind"), Smolka et al. (2014) failed to obtain significant semantic priming effects in purely visual (Experiment 1) and cross-modal (Experiment 2) tasks. However, in their Experiment 3 (purely visual), Smolka et al. (2014) added semantically related noun-noun pairs such as *Biene* "bee" → *Honig* "honey" and *Onkel* "uncle" → *Tante* "aunt", in addition to the semantically related verbs that were used in the previous experiments. Interestingly, with this change the semantically related verbs (as well as the nouns) showed significant facilitation.

In the present study, we implemented the following elements in order to promote the conditions for semantic priming. First, we included semantically related noun-noun pairs, as this was shown to have an effect on verb-verb priming in Smolka et al. (2014). This relates further to a large body of semantic priming literature that shows that priming effects increase in magnitude as the relatedness proportion increases (for an overview see Hutchison, 2007). Second, we included semantic associates that are nouns, as was done in De Grauwe et al. (2019), such that critical prime-target pairs consisted not only of verb-verb pairs but also of verb-noun pairs. Finally, as noted above, we presented primes and targets auditorily, which has been shown to result in larger effect sizes for semantic and associative priming compared to visually presented stimuli (Gomes et al., 1997; Hutchison, 2003).

2. Method

2.1. Participants

Participants were 28 adult native speakers of Dutch, most of whom were students or recent alumni of the University of Amsterdam. They reported having no reading, hearing, or other language disorders. Participants provided written informed consent prior to the start of the experiment, and they were paid a small fee for their participation. Ethical approval for the study was provided by the Institutional Review Board at the University of Pennsylvania, with protocol identification number #824771, and was further approved by the Ethics Committee Faculty of Humanities at the University of Amsterdam.

2.2. Materials

The critical stimuli consisted of 128 primes to 32 targets (see Table 1). We used a within-target design, in which response times to the same target across different

Table 1. Stimulus characteristics of opaque prefixed verb targets and the primes in the different conditions.

	Prime condition				Target
	Stem	Transparent	Opaque	Control	
Sample item	*halen*	*afhalen*	*herhalen*	*afdwalen*	*BRENGEN*
Translation	"take/get"	"take away/out"	"repeat"	"stray (off)"	"bring"
Mean prime frequency	3.24 (0.53)	2.08 (0.63)	2.27 (0.82)	1.90 (0.60)	–
Mean semantic score	–	5.48 (0.61)	1.92 (0.62)	–	–

Note: Semantic relatedness scores reflect the extent to which the transparent and opaque primes are related in meaning to their stem, on a scale of 1–7. Frequencies reflect Lg10CD measures as extracted from SUBTLEX-NL (Keuleers et al., 2010).
Standard deviations are given in parentheses.

prime conditions are measured. An advantage to this design is that individual differences among target words can be better controlled so that potential confounds based on specific target properties can be avoided (see e.g. Milin et al., 2018). In our experiment, prime conditions were formed by (i) prefixed verbs that are morphologically and semantically transparent (e.g. *afhalen* "take away/out"); (ii) prefixed verbs that are morphologically related but semantically opaque (*herhalen* "repeat"); (iii) the stems of the transparent and opaque prefixed verb primes, including the infinitival suffix (*halen* "take/get"); and (iv) prefixed verbs that are unrelated in meaning, morphology, and phonology to the targets and which served as the control condition (*afdwalen* "stray (off)"). The targets were semantic associates to the stem primes (*BRENGEN* "bring"). A full stimulus list can be found in the supplementary material.

2.2.1. Prime selection

The semantically transparent and semantically opaque prefixed verb primes were selected based on the semantic relatedness scores from a pre-test that was used in Creemers et al. (2020), which established the semantic relatedness between prefixed verbs and their stem. In the pre-test, 12 native speakers of Dutch were asked to rate the semantic relatedness of word pairs on a seven-point scale, with 1 being "completely unrelated in meaning" and 7 being "highly related in meaning". Transparent verbs had a mean semantic score that was higher than 4, and opaque verbs had a mean score lower than 3 in order to be included in the critical items (Table 1; see Creemers et al., 2020 for details). For the current experiment, we selected 32 transparent and 32 corresponding opaque verbs.

The stem primes consist of the morphological stems of the transparent and opaque primes, and are highly frequent simplex verbs which occur with the infinitival suffix *-en*. Mean frequencies for primes and targets are given in Table 1. The control primes are unrelated in meaning, morphology, and phonology to the stem of their corresponding transparent and opaque primes and to the target. All control primes are prefixed verbs.

2.2.2. Target selection

The semantically associated words that form the targets were selected using the Dutch Association Lexicon of the Small World of Words (SWOW) project[3] (De Deyne et al., 2013), the largest available network of word associations in Dutch. From the primary responses to stems ("cues"), we choose a highly associated word for each stem, while avoiding overlap in phonology or morphology (for instance, *breekbaar* "lit. break-able; fragile" was not picked as an associate for *breken* "break", even though the words are highly related in meaning). Moreover, we made sure that the selected targets were unrelated in meaning to the relevant opaque verbs (for instance, even though *water* "water" is highly related in meaning to *drinken* "drink", it was not used as a target since it is also related to *verdrinken* "drown"). We quantified word association strength as how often a word was offered as the primary response to the cue word, out of the total of primary responses to that cue word. Each cue had a total of 100 responses, but we excluded empty responses consisting of "x" which led to an average of 99.75 responses per cue.

Half of the targets (a total of 16) were verbs; the other half were nouns (15) or adjectives (1), as was determined by the dominant POS variable in SUBTLEX-NL (Keuleers et al., 2010), which gives the part of speech of the stimulus word with the highest frequency. The nouns/adjectives and verbs have comparable mean frequencies and word association strengths, as illustrated in Table 2.

2.2.3. Fillers and pseudo-words

In addition to the critical stimuli, fillers and pseudowords were included. A total of 120 filler words were

Table 2. Target characteristics, for the nominal/adjectival targets, verbal targets, and the combined set.

	Noun/Adj	Verb	Combined
Frequency	2.98 (0.54)	3.34 (0.57)	3.16 (0.57)
Association strength	0.29 (0.16)	0.33 (0.19)	0.31 (0.17)

Note: Mean frequencies are extracted from SUBTLEX-NL (Lg10CD; Keuleers et al., 2010). Association strenghts are calculated based on the primary responses (to stem primes) in the Dutch Association Lexicon (De Deyne et al., 2013).
Standard deviations are given in parentheses.

included. Of these, 60 words formed 30 semantically related noun pairs (e.g. *tak* “branch” → *boom* “tree”; *omelet* “omelet” → *ei* “egg”) to motivate semantic processing, as was shown to be effective in Smolka et al. (2014). While the majority of these items were nouns, we also included some adjectives. The semantically related filler pairs were selected from De Deyne and Storms (2008), who collected norms for 1424 Dutch words in a continuous word association task from over 10,000 participating individuals. In addition, 40 unrelated verbs (both prefixed and simple verbs) and 20 nouns were included. Following De Grauwe et al. (2019, Experiment 3), the proportion of related pairs in the existing words in the experiment (both fillers and critical stimuli) is 50%, since half of the critical items are semantically related in addition to half of the filler items.

Finally, we included 184 pseudo-words. We based these stimuli on Hanique et al. (2013), who constructed their pseudo-words by exchanging one or two letters in the stems of real verbs while preserving the phonotactic constraints and morphological structure of Dutch real verbs. Of the pseudo-words, 44 occurred with an existing prefix so that participants could not make a lexical decision based just on the first syllable. In addition, 90 pseudo-words were disyllabic and ended in the infinitival suffix *-en*, and an additional 50 pseudo-words did not end in *-en*. Half of the unrelated fillers were randomly combined with pseudo-words to form prime-target pairs. In total, each participant heard 368 stimuli.

2.3. Apparatus

The stimuli were recorded by an adult female native speaker of Dutch in a sound attenuated booth, using a high-quality microphone. Soundfiles were segmented using Praat (Boersma & Weenink, 2015) and normalised to a peak amplitude of 70 dB SPL. The task was implemented in PsychoPy2 (Peirce, 2007). Stimuli were presented auditorily through Sennheiser HD 280 PRO headphones.

2.4. Procedure

A continuous primed lexical decision task was used, in which participants were asked to make lexical decisions to all items. Primes and targets were presented auditorily and at immediate distance. The experiment consisted of four lists, with primes to the same target rotated according to a Latin Square design, such that each subject saw every target only once. We followed the standard practice in auditory semantic priming of using a relatively short inter-stimulus interval (ISI) to minimise strategic effects and tap into automatic semantic priming, while using a longer inter-trial interval (ITI) (see e.g. Gomes et al., 1997). The task had a random ISI between 300–400 ms, and a random ITI between 1100–1200 ms. The ISI and ITI were measured from the end of the sound file or participant response, whichever was later. Stimulus presentation was randomised (not affecting prime-target pairs), with a different order for each participant. The experiment consisted of three blocks with a self-administered break after each block, and a practice trial of 10 items at the beginning of the experiment. Items were randomly assigned to the different blocks.

Participants were tested individually in a quiet room. Participants were instructed that they would hear existing and non-existing Dutch words, and that they had to make a lexical decision to each word as fast and as accurately as possible. Responses of “Word” and “Non-word” were recorded from keyboard button presses. The experiment lasted on average for 12.44 minutes per participant.

3. Analysis and results

3.1. Analysis

The data were analysed as follows. Responses were coded for response type (word/non-word) and response time (RT; measured in ms from the onset of the sound file). Differences in duration of the sound files were included as a predictor in the model. One participant was removed due to an overall low accuracy across all stimuli (68%), after which the lowest overall accuracy was 91%. Trials with incorrect responses to primes or targets were discarded, which led to an exclusion of 23 data points out of 864 (32 targets * 27 participants) observations. We combined minimal a-priori data trimming with post-fitting model criticism (Baayen & Milin, 2010). All targets with outlier RTs (<100 ms and >2000 ms) were excluded, as well as the targets for which the prime had an outlier RT. This led to a further exclusion of 13 data points. The RT data were log-transformed, and removal of outliers was done for 5 individual subjects and 6 individual items for which Shapiro-Wilk’s tests for normality showed non-Normal distributions. This led to the further removal of 16 data points. In total, a-priori data trimming led to the exclusion of 29 observations, or 3.36%.

We analysed effects on log-transformed RT with linear mixed-effects models, using the `lme4` package (Bates et al., 2015, version 1.1-21) in the `R` environment (R Core Team, 2016, version 3.6.0). Random intercepts for subjects, primes, and targets were included. The following predictors were included in the model: Condition (Stem, Transparent, Opaque, Control), Part of Speech (PoS) of the target, Target frequency, Prime frequency, Target duration, ISI, Prime RT, and Trial. An interaction between Condition and PoS was included to examine whether priming effects are modulated by the target's Part of Speech (as was shown to be the case in a semantic priming study by Gomes et al., 1997). Condition was treatment coded with the Control condition as the reference level. PoS was sum-coded, so that the model tests the difference between the two factor levels (Schad et al., 2020), with verb as 1 and noun/adjective as -1. Target frequency, Prime frequency, Target duration, Trial, ISI and Prime RT were z-scored, and Prime RT was also log-transformed. The model was refitted after excluding data points with absolute standardised residuals exceeding 2.5 standard deviations (Baayen & Milin, 2010), which resulted in the exclusion of 26 observations. The results of the final model after model criticism are presented here. *P*-values were computed using the Satterthwaite approximation for degrees of freedom, as implemented in the `lmerTest` package (Kuznetsova et al., 2016, version 3.1-0). Significant *p*-values are reported at $p<0.05$.

Table 3. Mean response times to the targets (in ms), priming effects (in ms), and error rates for each condition.

Condition	RT target	Priming effect	Error rate
Control	869 (12.22)	–	3.24% (7/216)
Stem	804 (12.32)	65 (17.35)	1.85% (4/216)
Transparent	817 (12.25)	52 (17.30)	2.78% (6/216)
Opaque	835 (10.51)	34 (16.11)	2.78% (6/216)

Note: Standard errors for RT latencies are given in parentheses.

3.2. Results

An overview of the results is provided in Table 3 and in Figures 1 and 2. Model summary tables are provided in Tables 4 and 5.

The analysis of the log-transformed RT data (Table 4) reveals a significant difference between the Stem condition and the Control condition ($\beta = -0.067$, $p<0.001$). The model also indicates significant differences between the transparent condition and the control condition ($\beta = -0.053$, $p < 0.001$), and, crucially, between the opaque condition and the control condition ($\beta = -0.035$, $p = 0.026$). In other words, the results show significant priming effects for the semantic associates to the stems in all conditions, including the semantically opaque prefixed verb primes. This suggests that the meaning of the embedded stem is retrieved during the auditory processing of prefixed verbs, even when the stem's typical meaning does not play a role in the meaning of the opaque prefixed verb.

We performed a further planned comparison by relevelling the reference level of Condition to the semantically opaque condition (Table 5). While targets preceded by semantically opaque primes showed a numerically smaller priming effect compared to targets preceded by unprefixed stem primes and targets preceded by semantically transparent primes, the model does not reveal significant differences in the RTs to targets in the opaque and transparent conditions ($p = 0.219$) and between the RTs in the opaque and stem conditions ($p = 0.065$). The numerically smaller effects for

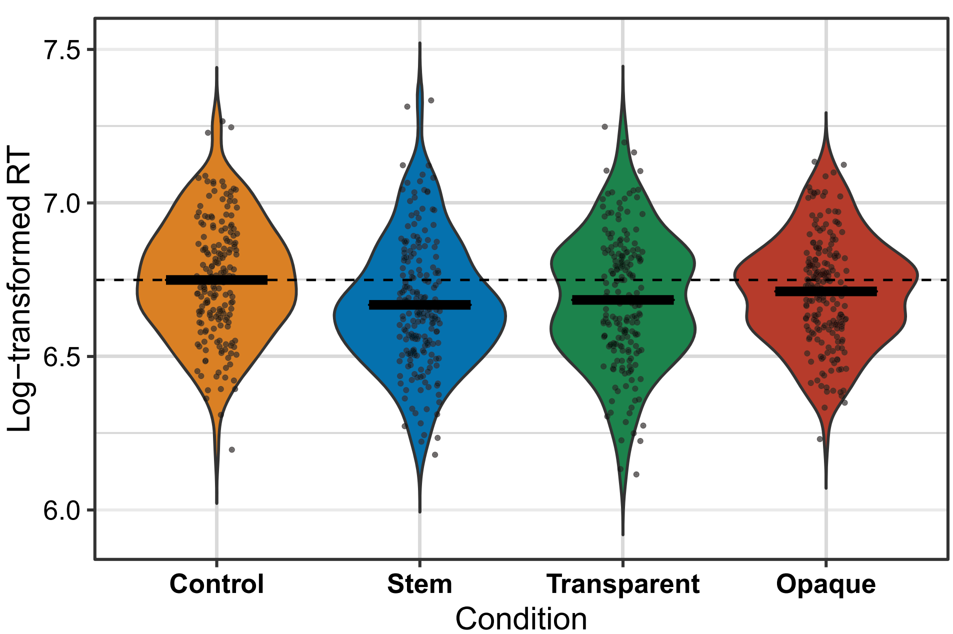

Figure 1. Violin plots of the log-transformed response times for the control, stem, transparent, and opaque conditions. Black horizontal bars represent condition means; the dotted line represents the mean in the control condition.

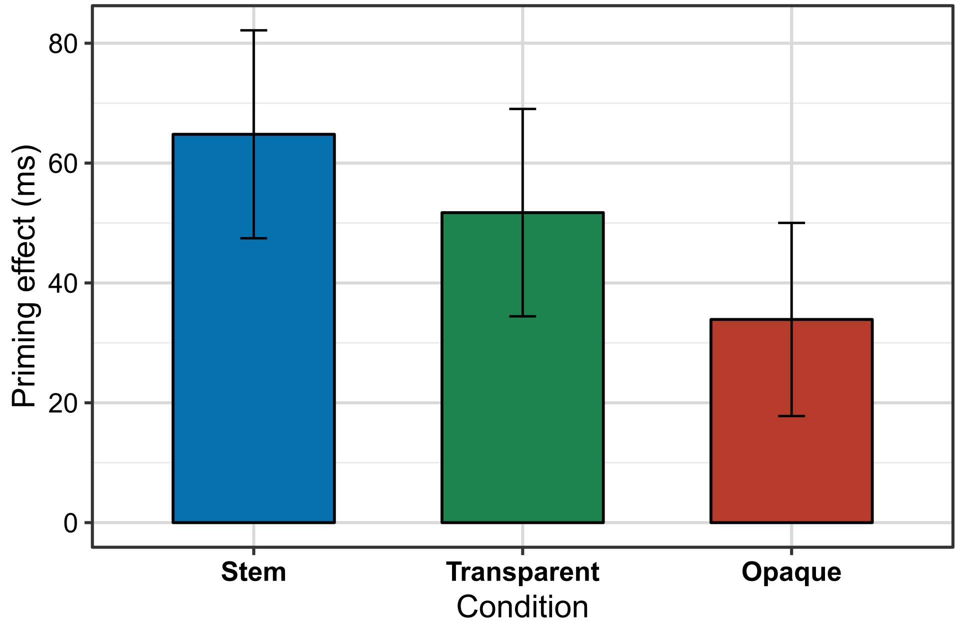

Figure 2. Priming effects (in ms) in the stem, transparent, and opaque conditions. Error bars represent ±1 standard error of the sampling distribution of differences.

semantically opaque primes raise interesting questions about the temporal dynamics of lexical-semantic retrieval, and whether the retrieved stem meaning in opaque forms is suppressed. This is further discussed in the next section.

The Part of Speech of the semantic associate that formed the target turned out to be a significant predictor ($\beta = -0.038$, $p = 0.014$), with faster responses to verb targets than to noun/adjective targets. This is illustrated in Figure 3. However, the interaction between Condition and PoS was not significant (Control–Stem: $p = 0.705$; Control–Transparent: $p = 0.099$; Control–Opaque: $p = 0.949$). This shows that, even though people responded faster to verb targets, priming effects were not influenced by the targets' Part of Speech.

Moreover, and as expected for a lexical decision task, the model reveals a significant effect of Trial number ($\beta = -0.022$, $p < 0.001$), showing that participants responded faster as the experiment progressed. The effect of Target duration was also significant ($\beta = 0.075$, $p < 0.001$), indicating that it took participants longer to recognise longer targets, as expected since RT was calculated from the start of the sound file. Similarly, the effect of Prime RT was significant

Table 4. Fixed effects of the predictors in the linear mixed-effect model for response latencies (log-transformed RT), with the reference level of Condition set to the Control condition.

Fixed effects	Estimate (*β*)	*t*-value	*p*-value
(Intercept)	6.743	268.791	**<.001**
Prime Condition (Control)			
Stem	−.067	−3.536	**<.001**
Transparent	−.053	−3.405	**<.001**
Opaque	−.035	−2.296	**.026**
Part of Speech (PoS)	−.038	−2.521	**.014**
Target Frequency	−.014	−1.208	.238
Prime Frequency	.014	1.833	.070
Trial Number	−.022	−4.895	**<.001**
ISI	−.002	−.475	.635
Target Duration	.075	6.762	**<.001**
Prime RT (log)	.045	8.150	**<.001**
Prime Condition (Control–Stem) x PoS	.006	.380	.705
Prime Condition (Control–Transp.) x PoS	.025	1.668	.099
Prime Condition (Control–Opaque) x PoS	.001	.065	.949

Note: Significant *p*-values ($p < 0.05$) are shown bold faced.

Table 5. Fixed effects of the predictors in the linear mixed-effect model for response latencies (log-transformed RT), with the reference level of Condition set to the Opaque condition.

Fixed effects	Estimate (*β*)	*t*-value	*p*-value
(Intercept)	6.708	271.389	**<.001**
Prime Condition (Opaque)			
Control	.035	2.272	**.026**
Stem	−.032	−1.871	.065
Transparent	−.019	−1.23	.219
Part of Speech (PoS)	−.037	−2.482	**.016**
Target Frequency	−.014	−1.208	.238
Prime Frequency	.014	1.833	.070
Trial Number	−.022	−4.895	**<.001**
ISI	−.002	−.475	.635
Target Duration	.075	6.762	**<.001**
Prime RT (log)	.045	8.150	**<.001**
Prime Condition (Opaque–Control) x PoS	−.001	−.065	.949
Prime Condition (Opaque–Stem) x PoS	.005	.319	.750
Prime Condition (Opaque–Transp.) x PoS	.024	1.619	.110

Note: Significant *p*-values ($p < 0.05$) are shown bold faced.

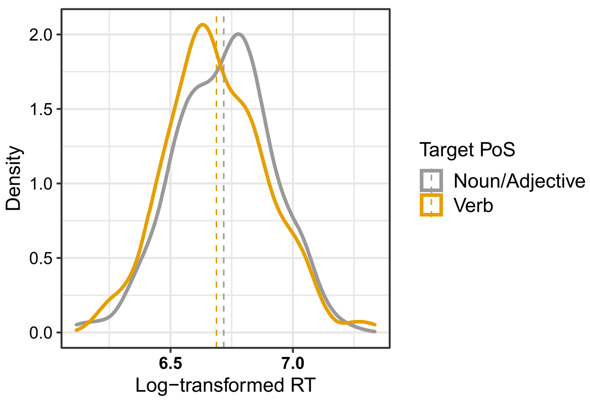

Figure 3. Log-transformed response times to verb versus noun/adjective targets. Vertical dotted lines represent means.

($\beta = 0.045$, $p < 0.001$), indicating that participants responded slower to targets after having taken longer to respond to the prime. The effect of PRIME FREQUENCY was marginally significant ($\beta = 0.014$, $p = 0.070$), showing that it took participants longer to recognise a target after hearing a higher frequency prime. The effects of TARGET FREQUENCY ($p = 0.238$), and ISI ($p = 0.635$) were not significant.

Finally, as suggested to us by a reviewer, we did a post-hoc robustness analysis in which degree of semantic relatedness was included as a continuous measure. This analysis recognises that a continuous gradient of semantic transparency forms a finer-grained characterisation of morphologically complex words than the dichotomous distinction between transparent and opaque words (see e.g. Marelli & Luzzatti, 2012). We subsetted the data to include only the transparent and opaque conditions, and fitted a linear mixed-effects model that included SEMANTIC TRANSPARENCY (with values between 1 and 7) rather than CONDITION; the other predictors and random effects structure were identical to the original model. We used the optimiser "bobyqa" to help with convergence issues, and data points with absolute standardised residuals exceeding 2.5 standard deviations were removed (excluding 8 observations). The model did not reveal a significant effect of SEMANTIC TRANSPARENCY ($p = 0.391$), showing that how related in meaning to their stem the prefixed verbs were judged to be in the norming study did not influence the response latencies to semantic associates of the stems. This supports the conclusion drawn based on the original model that the meaning of the embedded stem is retrieved during the processing of prefixed verbs, regardless of the meaning relatedness between that stem and the prefixed verb. The additional fixed effects were in line with the original model: TRIAL NUMBER ($\beta = -0.031$, $p < 0.001$), PRIME RT ($\beta = 0.036$, $p < 0.001$), and TARGET DURATION ($\beta = 0.086$, $p < 0.001$) were significant; marginally significant effects were found for PoS ($\beta = -0.025$, $p = 0.085$) and PRIME FREQUENCY ($\beta = 0.020$, $p = 0.068$). TARGET FREQUENCY ($p = 0.184$), ISI ($p = 0.151$), and the interaction between SEMANTIC TRANSPARENCY and PoS ($p = 0.338$) were not significant.

4. General discussion

The results show significant priming effects for the semantic associates in all conditions, that is, after stem primes (*halen* "take/get" → *BRENGEN* "bring"), after semantically transparent prefixed verb primes (*afhalen* "take away/out" → *BRENGEN* "bring"), and, crucially, after semantically opaque prefixed verb primes (*herhalen* "repeat" → *BRENGEN* "bring"). These findings provide evidence for *Possibility 2*: it appears that the lexical-semantic meaning of the stem is activated when opaque forms are processed. Relatedly, the findings converge with those from the stem priming literature, in providing evidence that opaque forms contain the same stem that occurs on its own and in transparent forms. This relates to the issue of *identity* as discussed in the Introduction: the results suggest that the stem seen in opaque verbs consists of the same morpheme as the unprefixed stem. However, careful consideration regarding what is driving these effects and their time-course is in order, and certain alternative explanations must be ruled out before these conclusions can be drawn. This will be the focus of this section. Moreover, our results differ from earlier semantic priming studies with Dutch and German prefixed verbs (De Grauwe et al., 2019; Smolka, 2019; Zwitserlood et al., 2005, 1996), which reported a lack of significant priming for the meaning of the stem in opaque forms. The difference in results is likely due to the auditory presentation of targets in our design, as discussed in more detail below.

4.1. Magnitude of priming effects

The priming effects obtained in our experiment are of a fairly large magnitude compared to priming effects in semantic priming studies with visually presented targets. Zwitserlood et al. (1996), for instance, found effects of at most 20 ms for visual semantic priming with unprefixed verbs (*bringen* "bring" → *HOLEN* "get, pick up"), and effects of around 10 to 30 ms for prefixed verbs. De Grauwe et al. (2019) found a semantic priming effect of 35 ms for transparent motor verbs (*PEN* "pen" → *opschrijven* "write down"), and Schreuder et al.

(2003) found priming effects of 27 and 26 ms. In contrast, we found a semantic priming effect of 65 ms for stem primes (*halen* "take/get" → *BRENGEN* "bring"), of 52 ms for transparent prefixed primes (*afhalen* "take away/out" → *BRENGEN* "bring"), and of 34 ms for opaque prefixed primes (*herhalen* "repeat" → *BRENGEN* "bring").

The difference in magnitude between the modalities is in line with earlier studies. In an overview, Hutchison (2003) concludes that semantic and associative priming experiments in the auditory modality have larger effect sizes than those in the visual modality. Indeed, previous auditory-auditory semantic priming experiments report effect sizes comparable or larger to those in our experiments. For instance, Moss et al. (1995) examined semantic priming effects with different types of semantic relations between concrete nouns in an auditory-auditory priming experiment with paired lexical decision. For words that were members of the same category, priming effects of 122 ms (e.g. *dog* → *CAT*) and 95 ms (e.g. *dish* → *PLATE*) were obtained, and for words that share functional properties, priming effects of 111 ms (e.g. *theater* → *PLAY*) and 105 ms (*hammer* → *NAIL*) were found. In an auditory-auditory continuous primed lexical decision paradigm similar to the one used in our experiment, White et al. (2020) found priming effects of 64 ms (200 ms ISI) and 52 ms (800 ms ISI) with a mix of different types of associates to targets (e.g. *CEILING* → *wall*, *WORST* → *terrible*). Gomes et al. (1997) directly compared semantic priming effects in both modalities, and also found much larger auditory (107 ms) than visual (19 ms) priming effects.

In sum, the size of semantic priming in our study is within the range reported in the literature for auditory-auditory semantic priming, which is greater than reported for visual studies. Considering that the magnitude of priming in the semantically opaque condition in our experiment is smaller than that in the semantically transparent condition (though not significantly different), it is not surprising that this effect did not reach significance in earlier visual (De Grauwe et al., 2019; Zwitserlood et al., 1996) and cross-modal (with visually presented targets; Smolka, 2019; Zwitserlood et al., 2005) semantic priming studies with prefixed verbs. Under the assumption that semantic processing does not actually differ between the two modalities, semantic effects, then, might be best studied in the auditory modality, especially when effects are expected to be small in magnitude, as for embedded stems in opaque prefixed verbs.

In the next section, we examine possible alternative explanations for the results, that involve homophonous stems and word embedding effects.

4.2. Homophony and embedding effects

As noted above, our results appear to support the idea emerging from the stem priming literature on German and Dutch prefixed verbs that opaque prefixed verbs contain the same stem that occurs by itself in unprefixed verbs and in transparent prefixed verbs (Creemers et al., 2020; De Grauwe et al., 2019; Smolka et al., 2009, 2014, 2015, 2019). However, in order for this conclusion to be drawn, two alternative explanations– both of which relate to our findings concerning semantic priming– need to be ruled out.

First, instead of the stem being the same in e.g. *halen* "take/get", *herhalen* "repeat", and *afhalen* "take away/out", it could be the case that there are multiple homophonous stems. If that were true, then *herhalen* would be morphologically complex, but would contain a stem that is accidentally homophonous with unprefixed *halen* and with the stem found in *afhalen*. Although accidental homophony is a phenomenon quite common in human language, there is little evidence for there being multiple homophonous stems in prefixed verbs. Prior results have shown that when a homophone is disambiguated prior to its presentation (e.g. *savings bank*), the activation of a competing meaning (*river bank*) is delayed on a subsequent trial (Pylkkänen et al., 2006). The presentation of one homophone, therefore, does not prime the meaning of the other homophone, while our results clearly show that the presentation of *herhalen* "repeat" facilitates the recognition of a meaning related to *halen* "take/get". These considerations are points of convergence with prior studies of morphological stem priming (Creemers et al., 2020; De Grauwe et al., 2019; Smolka et al., 2009, 2014, 2015, 2019) which showed robust facilitation of the stem after presentation of an opaque prefixed verb. Facilitation of *halen* "take/get" after the presentation of opaque *herhalen* "repeat" would be unexpected if these words involved two accidentally homophonous stems. In sum, this strongly suggests that *herhalen* and *halen* involve the same underlying morpheme, akin to polysemous words, for which it has been suggested that all senses are retrieved (cf. Beretta et al., 2005).

A second alternative explanation is that the activation of meanings related to the stem in opaque prefixed verbs arises due to a type of embedding effect that has been reported in spoken-word recognition. Words, and in particular polysyllabic words, typically contain other words as substrings or "unintended embeddings" (cf. McQueen et al., 1995). A study by Zhang and Samuel (2015) tested different types of embedded words in an auditory-auditory semantic priming experiment, and showed that certain types of carrier words (e.g.

hamster) significantly facilitated the recognition of words that are associated with words embedded in them (e.g. *PIG* for *ham*). This finding raises the possibility that meanings related to embedded *halen* "take/get" would be activated during processing of *herhalen* "repeat" because meanings of *substrings* that match lexical items are activated as their carrier words are processed; not because *herhalen* contains the morpheme *halen* per se. However, further results in Zhang and Samuel (2015) argue against this possibility. Their experiments manipulated the position of the substring (initial or final) and the proportion of the embedded word by syllable (1/3, 1/2, or 2/3). Crucially, the results showed a striking asymmetry: while initial embeddings (in bold) significantly primed semantic associates (***dig**nity* → *SHOVEL* (1/3); ***ham**ster* → *PIG* (1/2); ***commo**dore* → *PERIOD* (2/3)), no facilitation in reaction time was found with final embedded strings, regardless of the proportion of overlap (*nomi**nee*** → *KNEE* (1/3); *trom**bone*** → *DOG* (1/2); *pa**rental*** → *CAR* (2/3)).[4] A lack of semantic priming for final embeddings was also reported in a cross-modal study by Norris et al. (2006) (e.g. *se**date*** → *time*) (but see Vroomen & De Gelder, 1997).

Zhang and Samuel (2015) attributed the initial/final contrast to differences in the way that the whole word and the embedding are activated with the incremental arrival of the speech signal. To a first approximation, the idea is that when initial embeddings like *ham* are encountered in *hamster*, the embedded word is, due to its position in the word, able to achieve a high level of activation relative to the carrier word before the activation of the latter eventually predominates. In the case of final embeddings, though, the carrier word's activation level has already achieved a high level of activation when the embedding is encountered, with the result that the latter achieves a relatively low activation compared to that of the carrier word. As a result, effects stemming from its activation– like those associated with retrieval of lexical meaning– are not found. For present purposes, the most important point is that the prefixed prime conditions in the present experiment correspond to the final-embedding conditions in Zhang and Samuel (2015) (e.g. *her**halen***). Based on Zhang & Samuel's findings (and expectations derived from them), no facilitation is expected based on pure embedding effects. Therefore, the retrieval of the stem's semantics does not look like an effect of processing an embedded substring.[5]

4.3. Relation to stem priming

A further point concerns how the findings of this paper relate to prior work examining opaque and transparent prefixed verbs in constituent priming paradigms (e.g. *herhalen* → *halen*) (e.g. Creemers et al., 2020; De Grauwe et al., 2019; Smolka et al., 2009, 2014, 2015, 2019). To highlight the point in question, it is necessary to review the primary reason why studies examining possible *morphological* relatedness have examined opaque prefixed verbs in comparison with their transparent counterparts. As we noted in the introduction, this comparison is based on the premise that opaque verbs make it possible to rule out effects of semantic relatedness, and to zero in on the (putative) role of morphological relatedness, i.e. on effects of a shared morphological stem. Succinctly, the argument is that opaque forms are not lexico-semantically related to their stems; thus, indications of relatedness between opaque verbs and their stems would be evidence for a morphological relationship (assuming phonological relatedness is controlled for).

The findings of this paper are prima facie problematic for the premise that opaque verbs make it possible to rule out lexical-semantic relatedness effects across the board, as we find evidence for the retrieval of the stem's meaning, even in opaque forms. It is therefore at least in principle possible that prior constituent priming studies were in fact detecting this lexical-semantic effect, rather than the morphological effects of a shared stem. We believe, however, that there are clear indications that the facilitation seen with opaque verbs in prior stem priming studies cannot be driven *exclusively* by the kind of lexical-semantic effect that we report here. Prior constituent priming studies have often shown to be insensitive to semantic priming effects, as evidenced by a lack of priming in semantic control conditions. Smolka et al. (2014), for instance, reported a lack of facilitation for German semantically related pairs (*zuschnüren* "tie" → *binden* "bind") in purely visual and cross-modal paradigms, while semantically transparent (*zubinden* "tie") and semantically opaque (*entbinden* "deliver") prefixed verbs did prime their stem. Similarly, Creemers et al. (2020) also found no semantic priming (*verlenen* "give, grant" → *bieden* "offer") in a Dutch auditory-auditory paradigm, while, again, semantically transparent (*aanbieden* "offer") and opaque (*verbieden* "forbid") primes did produce significant effects. Morphological stem priming thus occurs under conditions in which semantic priming was not seen. In addition, when significant semantic effects were found, as for instance in Smolka et al. (2009, Experiment 2a/b), the semantic effects were significantly smaller than the effects in the semantically opaque condition (but see Smolka et al., 2014, Experiment 3). In an EEG study, Smolka et al. (2015) further showed that the effects induced by transparent prime-target pairs were much stronger than the N400 effect produced by pure semantic associations. The most straightforward interpretation of prior morphological stem priming studies is, therefore, that they derive from a morphological relationship (shared stem), not a semantic one.

In sum, it appears that contrasts reported in prior studies preclude the possibility that facilitation from opaque primes in prior stem-priming studies is driven solely by the stem meaning. At a minimum, though, the points raised in this section indicate that significant care must be taken in studying opaque forms.

4.4. Why retrieve a lexical meaning not present in the opaque word?

Why would the language processing system activate a stem meaning that does not play a role in the opaque prefixed verb itself?[6] There are (at least) two approaches that we believe could be explored. The first is that the activation reflects an automatic property of the system, namely that activation of a lexical item through morphological decomposition results in the retrieval of its lexical semantics. A second possibility is that the retrieval of the stem meaning reflects a strategy employed by the processing system, one that is grounded in properties of the Dutch verbal system. We discuss these approaches, which are not necessarily mutually exclusive, in turn.

A particular kind of (full) decompositional model (proposed and developed in the line of research represented by e.g. Stockall & Marantz, 2006; Taft, 1979, 2004; Taft & Forster, 1975, see also Embick, 2015; Marantz, 2013) provides one way of understanding the effect. In such models, complex words are processed in stages; the *decomposition* of such words into constituent parts is followed by the *activation* of those morphemes, which are then *recombined* in a way that represents the form/meaning of the entire object (see in particular Fruchter & Marantz, 2015; Taft, 2004). If retrieval of a lexico-semantic representation is an automatic part of this process, likely during the *activation* step, then we might expect to find effects of the stem meaning along the lines reported here. In terms of how this proposal relates to the (opaque) meaning of the entire word, the idea would be that the stem meaning would be retrieved when the stem morpheme is activated, and then subsequently suppressed or inhibited when the contextual meaning determined by the prefix is retrieved, something that occurs at the recombination stage. The hypothesised time course of activation and subsequent suppression could be probed with an ISI manipulation, along the lines of Schreuder et al. (2003) and Zwitserlood et al. (1996).

The second line of explanation outlined above is related to the first one, but would be compatible with a broader range of representational commitments, in that it would not require the particular representations and stages posited in the type of decompositional model discussed above. This type of explanation would make use of the idea that activation of stem meanings reflects a type of processing strategy, one that is driven by the general properties of the vocabulary of Dutch. As we noted in the introduction, a large part of the verbal system of Dutch is comprised of prefixed verbs; and, while prefixed verbs that have only opaque meanings have been the focus in this paper, the majority of prefixed verbs in Dutch have a transparent meaning. Given this vocabulary structure, it could be the case that the processing system attempts to create transparent meanings by default, and that part of this process involves the retrieval of the meaning of the stem. To a first approximation, the idea would be that retrieval of the stem meaning is effected as part of an attempt to compose it transparently with the meanings of the morphemes that it occurs with. Putting to the side the exact nature of the composition operation involved with prefixed verbs, it suffices to note that this kind of strategy-based explanation could be incorporated into theories that do not have the particular stages that are posited by the decompositional accounts mentioned above.

4.5. Concluding remarks

This study was designed to test whether the processing of opaque words involves the retrieval of only the whole word meaning, or whether there is evidence that the meaning of the stem is retrieved as well. Using Dutch prefixed verbs, the results from an auditory semantic priming experiment showed that the meaning of embedded morphemes (e.g. of the stem *halen* as "take/get") is retrieved after processing an opaque prefixed verb like *herhalen* "repeat". These results are significant in their own right, because most prior studies, using visually presented targets, failed to obtain significant semantic priming effects for the meaning of the stem in opaque forms (De Grauwe et al., 2019; Smolka, 2019; Zwitserlood et al., 1996, 2005, but see Schreuder et al., 2003). In contrast, we used a design in which both primes and targets were presented auditorily and which included particular properties that enhanced semantic priming.

These findings pave the way for a number of further questions concerning how meanings are represented and processed. At a basic level, they raise the question of why a meaning that does not play a role in the whole word is retrieved. We outlined two ways in which this effect might be understood, one in which the retrieval of transparent semantics could be seen as an automatic consequence of activating a morpheme (in line with a decompositional model of morphological processing), and a strategy-based approach in which the processing system attempts to create transparent meanings by default. A key question for further research is to determine how these approaches can be explored in ways that make different predictions.

A different direction that calls for further research is how the retrieval of lexical semantic meanings for auditorily presented complex words is structured temporally. With opaque forms, the retrieval of the stem meaning needs to occur *in addition* to the retrieval of the stored opaque meaning, which raises questions regarding the interaction of these meanings. One important question is whether the different meanings are retrieved in parallel (with, eventually, only the opaque meaning remaining after a certain point), or whether one meaning becomes available first. This question was addressed in a visual study by Schreuder et al. (2003), but due to the instantaneous (and not incremental) nature of visual presentation, it is possible that the time course of processing is compressed in visual word recognition, relative to auditory word recognition, making direct comparisons difficult.

Finally, the findings point to interesting discoveries about how words are processed. In particular, our findings suggest that retrieval of the stem meaning occurs even though the materials in question would allow this step to be by-passed in principle (this is *Possibility 2* in the introduction). Prefixed verbs differ from some other types of opaque words that have been examined because the element inducing the particular opaque meaning to be retrieved (i.e. the prefix) is encountered first in the speech signal. Thus, the processing system has the necessary information to retrieve only the opaque whole-word meaning (*Possibility 1*). The fact that it does not appear to do this is therefore highly significant in terms of what it reveals about word processing.

Notes

1. We use “semantic priming” as an umbrella term for semantic and associative priming. For discussion, see Neely (2012) and Hutchison (2003).
2. Semantic associates are represented in capital letters throughout the paper.
3. The Small World of Words project project maps word meaning in various languages. The methodology used is based on a continued word association task, in which participants see a cue word and are asked to give three associated responses to this cue word. The data can be viewed and downloaded from www.smallworldofwords.org/en/project/research.
4. With 2/3 embeddings Zhang and Samuel (2015) reported a priming effect in *accuracy* for both initial and final strings; the crucial point here is that no facilitation was found with final embeddings.
5. See Zhang and Samuel (2015) for further discussion of how this and related findings connect with findings on embedding from the prior literature where modality appears to play an important role.
6. Throughout this paper, we characterised the meaning of the stem as the “stem meaning”. However, another possible way of describing this effect is that the *most frequent* meaning associated with the stem is retrieved. We cannot distinguish between these possibilities here, as the simplex verbs in our materials are all highly frequent, such that it is almost certainly the case that the meaning of a given stem also happens to be the meaning that is most frequently found when tokens of that stem occur. A type of processing-strategy along these lines would then reflect a strategy according to which the processing system attempts to work with the most frequent meaning of a stem first.

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Data availability statement

The data that support the findings of this study are openly available on the Open Science Framework: https://osf.io/y7swa/.

Disclosure statement

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