Journal of Memory and Language 110 (2020) 104055

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Opacity, transparency, and morphological priming: A study of prefixed verbs in Dutch

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ARTICLE INFO

Keywords:
Morphological priming
Semantic opacity
Dutch prefixed verbs
Decomposition effects
Auditory word recognition

ABSTRACT

A basic question for the study of the mental lexicon is whether there are morphological representations and processes that are independent of phonology and semantics. According to a prominent tradition, morphological relatedness requires semantic transparency: semantically *transparent* words are related in meaning to their stems, while semantically *opaque* words are not. This study examines the question of morphological relatedness using intra-modal auditory priming by Dutch prefixed verbs. The key conditions involve semantically transparent prefixed primes (e.g., *aanbieden* 'offer', with the stem *bieden*, also 'offer') and opaque primes (e.g., *verbieden* 'forbid'). Results show robust facilitation for both transparent and opaque pairs; phonological (Experiment 1) and semantic (Experiment 2) controls rule out the possibility that these other types of relatedness are responsible for the observed priming effects. The finding of facilitation with opaque primes suggests that morphological processing is independent of semantic and phonological representations. Accordingly, the results are incompatible with theories that make semantic overlap a necessary condition for relatedness, and favor theories in which words may be related in ways that do not require shared meaning. The general discussion considers several specific proposals along these lines, and compares and contrasts questions about morphological relatedness of the type found here with the different but related question of whether there is morphological decomposition of complex forms or not.

1. Introduction

Theories of the mental lexicon differ substantially with respect to the role that specifically *morphological* representations and processing play in the comprehension and production of words. Much work in this area is framed as opposing theories that have morphological processing/representations and those that do not, often in ways that relate to the further question of whether or not there is morphological *decomposition*. The present paper addresses a distinct but related question concerning what types of factors are involved in *morphological relatedness*. In its simplest form, this is the question of whether words are related to one another in ways that are independent of semantics and phonology. Here, we will ask whether meaning overlap between words is a precondition for their relatedness, or whether words may be morphologically related despite not sharing a meaning.

A prominent tradition in theories of the mental lexicon makes regularity a precondition for relatedness. According to such theories, irregular words that appear to be morphologically complex are memorized in their full form in the mental lexicon, and, as such, have separate lexical entries from their putative stems. Irregularity, here, should be understood as irregular morpho-phonological forms (such as irregular allomorphy) and non-predictable meanings (semantic non-compositionality and opacity). In this type of model, for example, the compound *teacup*, which has a predictable or *transparent* meaning, is related to both *tea* and *cup*. The irregular *bellhop*, on the other hand, is not related semantically to either *bell* or *hop*; it is thus *opaque*. Theories that predict relatedness only for semantically transparent and phonologically regular forms have been proposed in very different looking architectures. For example, there are connectionist models which argue that morphological effects should be reduced to shared or interacting semantics and phonology (e.g., Gonnerman, Seidenberg, & Andersen, 2007; Seidenberg & Gonnerman, 2000); supralexical models which argue that morphemes may be accessed only after whole-word access (e.g., Diependaele, Sandra, & Grainger, 2005; Giraudo & Grainger, 2001, 2003); and (parallel) Dual-Route models, which assume that both full-form based processing and decompositional processing are available routes, with (ir)regularity determining which path is taken (e.g., Baayen, Dijkstra, & Schreuder, 1997; Bertram, Laine, Baayen, Schreuder, & Hyönä, 2000; Burani & Caramazza, 1987; Burani & Laudanna, 1992; Caramazza, Laudanna, & Romani, 1988; Frauenfelder

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https://doi.org/10.1016/j.jml.2019.104055
Received 1 October 2018; Received in revised form 10 September 2019; Accepted 10 September 2019
Available online 27 September 2019

& Schreuder, 1992; Schreuder & Baayen, 1995).

While the views summarized above differ on some points, they share the crucial claim that the relation between an opaque word and its apparent stem is different from the relation between a transparent word and its stem. These views contrast with approaches that do not make morphological relatedness effects contingent upon semantic transparency. In fully decompositional models, for example, *bellhop* is related to both *bell* and *hop* because it consists of these two parts, in spite of semantic opacity (Smolka, Preller, & Eulitz, 2014; Smolka, Libben, & Dressler, 2019; Stockall & Marantz, 2006; Taft, 1979, 2004; Taft & Forster, 1975; cp. Marantz, 2013; Embick, 2015). Such models predict these relatedness effects because they are centered on the idea that morphological complexity implies *independent* morphological processing and representation– that is, morphological relatedness can exist without semantic overlap. Importantly, though, similar relatedness effects might also be captured in learning models (Baayen, Milin, Đurđević, Hendrix, & Marelli, 2011; Baayen, Chuang, Shafaei-Bajestan, & Blevins, 2019; Milin, Feldman, Ramscar, Hendrix, & Baayen, 2017) that begin with very different architectural assumptions than decompositional models. We return to this point in our general discussion.

The present study probes the question of morphological relatedness with the use of prefixed verbs in Dutch. Semantically speaking, prefixed verbs produce meanings that may be *transparent* or *opaque*. To illustrate, a Dutch verb like *bieden* ('offer') may combine with the particle *aan* to form the transparently related *aanbieden* ('offer'), and with the prefix *ver-* (which has no straightforward meaning, although there are some sub-patterns in its use; see Lieber & Baayen, 1993) to form *verbieden* ('forbid'). This verb is semantically opaque in the sense that its meaning cannot be predicted from the meaning of its parts. The words *bieden* and *verbieden* are morphologically related: for instance, they both share the same unpredictable allomorphy in the past tense and participle forms. However, and given their lack of semantic overlap, a diagnostic beyond shared allomorphy is required in order to draw any strong conclusions about their relatedness, since their formal identity could be a historical accident.

A potential diagnostic for morphological relatedness is provided by morphological priming. For example, if a prime *teacher* produces significant facilitation for a target *teach*, this is often taken as evidence for morphological relatedness between the two words: informally, they both involve the word *teach*. Of course, any interpretation of this type must take into account the fact that *teacher* and *teach* are also semantically and phonologically (or orthographically) related, such that putative effects of morphological relatedness could be attributed to these other types of representations, not morphological processing or decomposition per se. It is in the light of this observation that the significance of opaque forms can be seen clearly. With an opaque prefixed verb like Dutch *verbieden* ('forbid'), semantic relatedness is not an issue for interpreting findings since, crucially, the meaning of the complex form shows no or only very little overlap with that of its stem. To the extent that formal (phonological or orthographic) relatedness can be eliminated from consideration through the use of controls, opaque primes offer a window into specifically morphological representations and processing.

We report the results from two intra-modal auditory priming experiments examining Dutch prefixed verbs. Morphological priming is investigated by manipulating the semantic and phonological relatedness of prime-target pairs. The crucial question addressed is whether or not there are morphological representations and processes that are independent of phonology and semantics. Specifically, we test whether semantic overlap forms a necessary condition for morphological relatedness between words, or whether morphological priming effects can be obtained in the absence of semantic compositionality, e.g., whether a complex verb like *verbieden* ('forbid') primes its stem *bieden* ('offer').

1.1. Prior work on 'semantically opaque' affixed forms

An important background to the present paper is the observation that the experimental literature on opaque forms shows contradictory findings for even closely related languages. For instance, morphological processing is said to be influenced by semantic transparency in English and French (Feldman, Soltano, Pastizzo, & Francis, 2004; Gonnerman et al., 2007; Longtin, Segui, & Halle, 2003; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rastle, Davis, Marslen-Wilson, & Tyler, 2000), but not in German (Smolka, Komlosi, & Rösler, 2009; Smolka et al., 2014; Smolka, Gondan, & Rösler, 2015; Smolka et al., 2019) and various Semitic languages (Boudelaa & Marslen-Wilson, 2004; Boudelaa & Marslen-Wilson, 2015; Feldman & Bentin, 1994; Frost, Forster, & Deutsch, 1997; Ussishkin, Dawson, Wedel, & Schluter, 2015).

A related complexity, one that might, in part, be responsible for the inconsistent cross-linguistic findings, is that prior investigations have been motivated by at least two distinct types of questions, and have employed different types of stimuli accordingly. The first research direction is one that focuses on orthography-based decomposition of pseudo-derived forms such as *corner*, which shows only an apparent morphological relation to *corn*. The second research direction looks at semantically opaque forms that might be decomposed on the basis of true morphological structure. A careful distinction between these types of questions, and the stimuli used in the different types of studies, is essential to understanding which words might or might not be related in the mental lexicon.

1.1.1. Pseudo-derived forms

A first line of research investigates the processing of *pseudo-derived* words like *corner*. While it is standardly assumed in the literature that this word is not a morphological derivative of *corn*, it can nevertheless be parsed into *corn* and *er*, a string that is orthographically identical to an independently occurring affix in the language (*-er*). Stimuli of the pseudo-derived type have been used in a wide range of masked priming studies, in which the prime is unavailable for conscious report due to short prime exposure. Early studies have argued in favor of a semantically blind mechanism of pre-lexical morpho-orthographic decomposition (Beyersmann et al., 2016; Diependaele, Sandra, & Grainger, 2009; Diependaele et al., 2005; Longtin et al., 2003; Marslen-Wilson, Bozic, & Randall, 2008; McCormick, Rastle, & Davis, 2008; Rastle et al., 2000; Rastle & Davis, 2003; Rastle, Davis, & New, 2004, i.a.), as both *farmer* → *FARM* and *corner* → *CORN* led to significant priming effects. At the same time, no such effects were found for *brothel* → *BROTH*, where, crucially, the string *el* does not form a potential suffix.

A different line of work, with different experimental designs and statistical analyses, has challenged these *form-then-meaning* accounts. Responses to semantically transparent pairs were shown to be significantly faster than responses to pseudo-related pairs in Feldman, O'Connor, and del Prado Martín (2009) and Feldman et al. (2015) (see also Andrews & Lo, 2013), and in addition, effects for pseudo-related pairs (*corner* → *CORN*) were reported to be equal to orthographically related pairs (*cornea* → *CORN*) in Milin et al., 2017. Moreover, it has been shown that semantic effects emerge early in the word recognition of transparent derived and pseudo-derived forms (Schmidtke, Matsuki, & Kuperman, 2017). These results are compatible with a *form-and-meaning* account, in which word recognition involves the simultaneous access of morphological and semantic information. However, the sequential *form-then-meaning* position has been defended in important neuro-imaging work (Lavric, Rastle, & Clapp, 2011; Lavric, Elchlepp, & Rastle, 2012; Whiting, Shtyrov, & Marslen-Wilson, 2014), which offers a time-sensitive method that allows investigation of the specific temporal ordering of different types of analysis during visual word recognition. The matter thus remains somewhat open, and will not be our central concern here.

1.1.2. Opaque forms

In this paper, our focus is not on pseudo-derived words, but instead on words that are morphologically derived, but have no semantic relation to their stem. We refer to these as *opaque* (see Feldman et al., 2015, p. 2; footnote 1). As a working definition, word W_2 is opaque with respect to word W_1 when W_2 consists of W_1, plus an element that is an affix in the language, *and* when there is at least some evidence for these words being related. Different factors can be considered in assessing evidence for a possible morphological relation. A shared pattern of idiosyncratic morphophonology in the form of allomorphy might play this role. For example, it might be hypothesized that the verbs *understand* and *withstand* share the stem *stand* that also occurs by itself as a verb, since all three verbs have the same, idiosyncratic past tense form *stood* (cf. Aronoff, 1976). Crucially, no evidence for morphological relatedness exists for pseudo-derived words.

For the reasons outlined earlier, the point of looking at opaque stimuli is that there is no evidence from meaning for relatedness. The behavior of opaque and transparent forms have typically been investigated in overt priming studies (as opposed to masked), in which primes are consciously perceived under visual priming at a long Stimulus Onset Asynchrony (henceforth SOA), or with auditory primes. Studies of this sort have led to different conclusions.

For English and French, it has been argued that only semantically transparent primes facilitate target processing in overt priming experiments. In English, morphologically and semantically related prime-target pairs (*departure* → *depart*) show significant effects regardless of the SOA used (43, 72, and 230 ms), while morphologically related but semantically unrelated pairs (*apartment* → *apart*) show priming only at the shortest SOA (Rastle et al., 2000). Also, in cross-modal priming experiments in English and French, priming is obtained for semantically transparent pairs, but not (or to a significantly smaller extent) for semantically opaque pairs (Feldman et al., 2004; Gonnerman et al., 2007; Longtin et al., 2003; Marslen-Wilson et al., 1994). Similar effects have been shown for Serbian (Feldman, Barac-Cikoja, & Kostić, 2002).

The results for English and French contrast starkly with findings for Semitic languages with non-concatenative morphology, such as Arabic (Boudelaa & Marslen-Wilson, 2004, 2005, 2015), Hebrew (Feldman & Bentin, 1994; Frost et al., 1997, but see Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson (2000) who find a significant difference between opaque and transparent conditions), and Maltese (Ussishkin et al., 2015). In these languages, robust morphological priming effects are obtained in the absence of semantic transparency. In Arabic cross-modal priming, for example, prime-target pairs of deverbal nouns sharing a root morpheme ({dxl}) which are semantically transparent ([*madxalun*] 'inlet' → [*duxuulun*] 'entry') show a priming effect of equal magnitude as semantically opaque pairs ([*mudaaxalatun*] 'conference' → [*duxuulun*] 'entry') (Boudelaa & Marslen-Wilson, 2015).

Importantly, recent studies on German prefixed verbs (Smolka et al., 2009, 2014, 2015, 2019) show that this pattern of results is not restricted to languages with non-concatenative morphology. In a series of overt visual and cross-modal priming experiments (Smolka et al., 2014), both semantically transparent (*zubinden* 'tie' → *binden* 'bind') and semantically opaque (*entbinden* 'deliver' → *binden* 'bind') derivations significantly facilitate responses relative to the unrelated condition, while neither semantically related synonyms (*zuschnüren* 'tie' → *binden* 'bind') nor form-related pairs (*abbilden* 'depict' → *binden* 'bind') differ from the unrelated condition.

On the face of it, the study of opaque words has produced a contradictory set of findings. However, some additional factors must be considered in assessing the apparent cross-linguistic differences. This is particularly the case with the languages argued to show facilitation for transparent but not opaque primes, such as English and French.

For English, matters of morphological relatedness may be obscured by complexities of the language that are the result of its history. Specifically, a large part of the vocabulary of English is borrowed from different Latinate languages. The Latinate part of English contains many words that look like they might be morphologically related (and which are often related etymologically), and many of the commonly used words in English priming studies are from the Latinate part (e.g., *successor*, *casualty*, *designate*; used in Feldman et al., 2004; Marslen-Wilson et al., 1994; Rastle et al., 2000). However, the synchronic status of many of these words in the minds of speakers is unclear. It is plausible that the Latinate part of the vocabulary is represented and accessed in a way that is qualitatively distinct from the Germanic vocabulary. For instance, studies of the development of knowledge of English derivational morphology show that much of it is acquired quite late, continuing to improve throughout adolescence and into adulthood, and that mastery of derivational morphology involves a longer, more open ended course compared to inflectional morphology (Anglin, 1993; Derwing & Baker, 1986; Duncan, Casalis, & Colé, 2009; Mahony, Singson, & Mann, 2000, Singson et al., 2000, i.a.). It is, hence, possible that some of the words classified as opaque in previous studies on English are actually better considered as pseudo-derived, with consequences for morphological priming.

For French, it is not clear that the stimuli have been classified in ways that correctly reflect the pseudo-derived versus opaque distinction. The Longtin et al. (2003, Experiment 2) study, for example, includes 'opaquely affixed' (*rater* 'to miss' → *rat* 'rat') and 'pseudo-affixed' forms (*traiter* 'to treat' → *trait* 'feature'), but uses these terms in a different way than we do. For Longtin et al. (2003), the distinction is meant to reflect the idea that 'pseudo-affixed' forms are connected neither semantically nor etymologically, while 'opaquely affixed' forms share an etymological connection, but are no longer related semantically. However, there is no reason to believe that this distinction is real for speakers of French, as it is unlikely that the etymological status of the 'opaque' words has psychological relevance and is part of what is represented in an individual's mental lexicon. Since there is no evidence for synchronic morphological relatedness between primes and targets in either of these conditions, it seems likely that both types of words are pseudo-derived. The absence of cross-modal priming in the opaque condition is, therefore, unsurprising.

We take away two main points from this prior work: first, the need to be clear about the pseudo-derived versus opaque distinction; and second, the fact that there is a need for more systematic investigation of opaque affixation in additional languages.

1.2. Dutch complex verbs

Our study of Dutch prefixed verbs looks directly at the effects of semantic transparency and opacity on morphological relatedness. Similar to German complex verbs (Smolka et al., 2009, 2014, 2015, 2019), Dutch complex verbs are prefixed with a separable or inseparable prefix,[1] and are productive and frequently used. In contrast to pseudo-derived words like *corner*, Dutch prefixed verbs are true morphological derivatives of their stems. Synchronic evidence for their morphological relatedness comes from the fact that complex verbs and their stems share irregular allomorphy. Many of the stems of prefixed verbs show unpredictable allomorphy in their preterite and past participle forms, a manifestation of the strong/weak verb distinction that is a property of Germanic languages. Crucially, prefixed verbs show the

[1] It is common to refer to separable prefixes as 'particles'. However, some of the affixes that are typically referred to as particles, like *aan*, may in fact occur as inseparable prefixes. An example of this is the prefixed verb *aanschouwen* ('see'), for which the prefix and verb are inseparable in main clauses, even though *aan* is not one of the common prefixes *be-*, *ver-*, or *ont-*. Therefore, in this paper, we use the terms separable versus inseparable prefixed verbs, rather than particle and prefix verbs.

same patterns of allomorphy as their stems, independent of semantic transparency or opacity (e.g., *bieden* 'offer' ~ *boden* 'offered'; *aanbieden* 'offer' ~ *aanboden* 'offered'; *verbieden* 'forbid' ~ *verboden* 'forbade'). Many prefixed verbs (that is, the irregular ones) thus provide morphophonological evidence for language learners that they are related to their unprefixed stems.

Dutch complex verbs provide an ideal test case to see whether morphological priming occurs in the absence of semantic compositionality, as these verbs may differ in meaning relatedness between the stem and the complex verb from fully transparent to fully opaque. For instance, *optrekken* ('pull up'), *uittrekken* ('remove, take off'), and *vertrekken* ('leave') all take *trekken* ('pull') as their stem but differ from fully transparent to fully opaque.

Morphosyntactially speaking, the prefixes are of two types: separable ones, which appear in a different position from the verb in 'verb second' clauses, and inseparable ones, which always appear prefixed to the verb stem. Importantly, it is not the case that there is a one-to-one relation between (in)separability of the prefix and semantic transparency/opacity of the complex verb, as inseparable and separable prefixes are both associated with transparent and opaque meanings. For instance, while the inseparable prefix *ver-* with *bieden* ('offer') results in a semantically opaque complex verb *verbieden* ('forbid'), the same inseparable prefix with *krijgen* ('get') results in a semantically transparent complex verb *verkrijgen* ('get, obtain'). Similarly, while *aanbieden* ('offer') with the separable prefix *aan* is semantically transparent, the same prefix with *breken* ('break') results in the semantically opaque verb *aanbreken* ('open, begin').

Related to the cross-linguistic differences discussed above, a study by Zwitserlood, Bolwiender, and Drews (2005, Experiment 2) is often referred to as showing that Dutch behaves like French and English in the sense that morphological priming is dependent on semantic overlap (see e.g., Amenta & Crepaldi, 2012; Hall et al., 2016; Smolka et al., 2014). A closer look at this study, however, shows that this particular conclusion is not warranted. The experiment in question uses sentence primes to activate the *conceptual* representation of (the stem of) the complex verb, and therefore investigates *semantic* rather than morphological priming of prefixed verbs. The question posed is whether a sentence like *hij slingerde haar de meest gemene dingen naar het hoofd* ('he shouted all sorts of mean things when talking to her') activates the *conceptual* representation of the complex verb *uitschelden* ('verbally abuse'), which does not occur in that sentence. This type of experiment is not intended to probe morphological processing and representation per se; instead, it is directed at concepts, associated either with an entire sentence, or with a prefixed verb. The results in Zwitserlood et al. (2005) indicate that there might be a difference between transparent and opaque prefixed verbs, but this difference relates to the activation of conceptual representations, not to morphological representations.

A study by Schreuder, Burani, and Baayen (2003) does look at morphological effects for opaque words in Dutch, and suggests that at least in Dutch low-frequency morphologically complex but semantically opaque words (such as *branding* 'surf, the rolling and splashing of the waves', which consists of two high-frequency constituents: *brand* 'fire, to burn' and the nominalizing suffix *-ing*), the component constituents are activated. However, a semantic priming experiment in the same paper also suggests that the first meaning to become available is the opaque (and appropriate) full-form meaning, and that the transparent reading (the meaning that is a possible reading morphologically, but that is not used in Dutch) emerges only later in time. Eye-tracking studies with Dutch compounds (Kuperman, Schreuder, Bertram, & Baayen, 2009) and suffixed words (Kuperman, Bertram, & Baayen, 2010) also suggest that whole-word effects are present from the earliest fixation onward, but that both full forms and constituent morphemes play a role in the processing of complex words.

Finally, a recent study by De Grauwe, Lemhöfer, & Schriefers (2019) shows significant morphological priming effects for Dutch separable prefixed verbs that are semantically transparent (*opschrijven* 'write down' → *schrijven* 'write') and semantically opaque (*toekennen* 'award' → *kennen* 'know') in an overt visual priming paradigm. In addition to the effects of semantic transparency, this study also manipulates the motor-relatedness of the simple verb constituent (the degree to which a word refers to a movement performed with specific muscles), following a specific line of reasoning from fMRI studies. While morphological effects seem independent of semantic transparency in these experiments, a semantic stem priming experiment shows significant semantic priming effects only for transparent motor verbs (*pen* 'pen' → *opschrijven* 'write down'), but not for semantically opaque or non-motor-related words.

However, the experimental design in De Grauwe et al. (2019) does not incorporate phonological and semantic control conditions. Therefore, the results remain suggestive, as alternate explanations are available for the reasons discussed above. The design in the present study differs from De Grauwe et al. (2019) in some crucial ways. First, instead of using a between-items design in which targets differ across priming conditions, we use a within-items design. This allows us to compare response times to the same targets across conditions, as the same target is used with a different prime in each condition. Second, we include phonological and semantic conditions to investigate whether any obtained morphological effects are in fact due to form and/or meaning overlap.

Taken together, prior work provides some suggestions as to how the opaque/transparent distinction affects the representation of Dutch words, but does not establish definitive conclusions on this point. Therefore, in the present study, we further investigate the effect of semantic transparency on morphological processing in Dutch prefixed verbs.

1.3. The present study

While most previous studies have addressed the issue of morphological processing by investigating the visual identification of target words (in masked, overt, and cross-modal paradigms), we investigate auditory word recognition. Although less commonly used in priming paradigms, auditory presentation has been shown to successfully probe many aspects of lexical representation (Bacovcin, Goodwin Davies, Wilder, & Embick, 2017; Balling & Baayen, 2008; Goodwin Davies et al., submitted for publication; Kouider & Dupoux, 2009, Wilder, Goodwin Davies, & Embick, 2019, i.a.). Examining the effects of transparency/opacity in the auditory modality is important for multiple reasons.

First, and most basically, the auditory modality is viewed as the most natural one for spoken language. The acquisition of oral language precedes the acquisition of written language, and speaking and listening are seen as 'primary' linguistic activities that secondary activities such as reading and writing are parasitic upon (e.g., Mattingly, 1984).

Second, the two modalities have a very different temporal structure. Unlike visual word recognition, in auditory word recognition the acoustic signal unfolds over time, which has consequences for lexical access. For instance, the Cohort model (Marslen-Wilson, 1984) assumes that the unfolding phonological input progressively narrows down the set of possible candidates (the cohort), until a Uniqueness Point is reached at which a word's cohort is reduced to a single member. For morphologically complex words, a second critical point in auditory comprehension has been shown to exist: the Complex Uniqueness Point, which is the point at which the complex word deviates from its morphological competitors (Balling & Baayen, 2008, 2012). Crucially, due to the incremental nature of the auditory word processing, the pieces that make up a multi-morphemic stimulus become available to the listener at different, specifiable times (Wurm, 2000), and the listener does not have access to the stem and affix of a complex word at the same time. In contrast, with visually presented words, the letters that make up the word are simultaneously presented, and eye-tracking studies show that many complex words are read with one fixation only (for an overview see Bertram, 2011), such that stems and affixes may be processed at the same time.

A third reason for examining auditory processing is that there is some evidence suggesting crucial differences in the effects that are detected in the different modalities. One case in point is the fact that masked priming effects for stimuli like *corner* → *corn* have been argued to be orthographically driven (Rastle et al., 2004; Rastle & Davis, 2008). Another case is the comparison between repetition priming (e.g., *frog* → *frog*) and morphological priming (e.g., *frogs* → *frog*), for which some studies report identical facilitation (Forster, Davis, Schoknecht, & Carter, 1987; Stanners, Neiser, Hernon, & Hall, 1979), while others report greater facilitation for repetition priming than for (inflectional) morphological priming (Kouider & Dupoux, 2009). As discussed in Wilder et al. (2019), the apparent contradiction might arise due to differences in modality: the studies reporting no difference between repetition and morphological priming employ visual stimuli, whereas those reporting a difference are auditory. The differences in question might very well be related to the contrasts between (near-) simultaneous and incremental arrival of the word mentioned above.

In the present study, we report on two experiments investigating Dutch prefixed verbs that are (i) morphologically and semantically related, (ii) morphologically related but semantically opaque, (iii) phonologically related, but semantically and morphologically unrelated, (iv) semantically related, but morphologically and phonologically unrelated, and (v) unrelated controls which function as our baseline. In Experiment 1, prime–target pairs are manipulated with respect to their morphological, semantic, and phonological relatedness in an immediate priming paradigm. In Experiment 2, we add a semantic condition, and manipulate the number of intervening items between prime and target. We use the experimental design used in Smolka et al. (2014), but due to the change in modality, we include a phonological condition rather than an orthographic condition, which serves to control for the potential effects of rhyme priming (see e.g., Norris, McQueen, & Cutler, 2002). In addition, we make use of a continuous lexical decision task, rather than a paired presentation of primes and targets with responses only to the latter. This minimizes the difference between primes and targets and therefore makes pairings and thus conditions under investigation less apparent to participants.

2. Experiment 1

The aim of the first experiment is to investigate the role of morphological structure in the lexical representation of complex verbs in Dutch, while teasing apart semantic, phonological, and morphological effects. Our research question is as follows: does a morphologically complex verb in Dutch prime its stem, and if so, what is the contribution of semantic and phonological overlap to these priming effects? While any theory predicts priming effects for targets with primes that are both morphologically and semantically related, priming effects for primes that are morphologically but not semantically related to their target are expected only if morphological processing is independent of semantic and phonological overlap. Moreover, if morphological effects are different from mere phonological overlap, we expect to obtain priming effects in the morphologically related condition that are significantly larger in magnitude than the effects in the phonological condition.

2.1. Method Experiment 1

2.1.1. Participants

Participants were 32 adult native speakers of Dutch, most of whom were students or recent alumni of the University of Amsterdam (mean age = 27.75; sd = 8.42). All participants were raised monolingual, and reported having no reading, hearing, or other language disorders. Some of the participants were recruited through www.proefbunny.nl, a website for participant recruitment. Participants were paid a small fee (5 euros) for their participation.

Table 1
Conditions and example critical items Experiment 1, for the target (the stem + infinitival suffix) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Phonologically related (Ph), and Control (C) conditions.

Target	MS prime	M prime	Ph prime	C prime
bieden	*aanbieden*	*verbieden*	*bespieden*	*opjagen*
'offer'	'offer'	'forbid'	'spy'	'hurry, rush'
schieten	*beschieten*	*opschieten*	*begieten*	*bezoeken*
'shoot'	'fire on/at'	'hurry up'	'pour over'	'visit'
werpen	*afwerpen*	*ontwerpen*	*aanscherpen*	*uitdraaien*
'throw'	'throw off'	'design'	'sharpen'	'print out'

2.1.2. Materials and design

The critical stimuli that form the targets in the first experiment are 36 base verbs that are high frequency simplex verbs. Each target was combined with four primes, resulting in 144 prime-target pairs. All primes were complex verbs, formed with a separable or inseparable prefix. We do not predict a difference in processing between the two types of prefixes (following Smolka et al., 2019, who show equally robust morphological processing for inseparable and separable prefixed verbs), but we include this information as a predictor in our model. Both types of prefixes occur in every prime condition. Prime-target relations are as follows: morphologically and semantically related (MS; e.g., *aanbieden* 'offer' → *bieden* 'offer'), morphologically related but semantically opaque (M; e.g., *verbieden* 'forbid' → *bieden* 'offer'), phonologically related (Ph; *bespieden* 'spy' → *bieden* 'offer'), and controls (C; e.g., *opjagen* 'hurry, rush' → *bieden* 'offer') which serve as the baseline and are unrelated in morphology, meaning, and phonology to their target. In the phonological condition, the stem of the prime and the target rhyme: they only differ in their onset consonant or consonant cluster, while sharing the rhyme. Table 1 presents examples of the stimuli used. The full stimulus list can be found in the appendix.

To establish the semantic relatedness between primes and targets, a semantic relatedness pre-test was conducted with at least two candidate complex verbs for every target base verb. The details of this pre-test can be found in the appendix. Frequencies for all primes and targets were extracted from the SUBTLEX-NL database (Keuleers, Brysbaert, & New, 2010). Primes were matched for frequency as much as possible. Neighborhood densities for the targets are extracted from CLEARPOND-Dutch (PTAN values, Marian, Bartolotti, Chabal, & Shook, 2012). Both frequencies and neighborhood densities for targets are added as predictors in the regression model. Table 2 provides the mean semantic scores from the pretest and the mean frequencies in the four conditions for primes and targets.

To prevent strategic effects, we furthermore included 308 filler pairs, so that critical item pairs make up only 10.47% of all items. Fillers consisted of 50% real words and 50% non-words. The non-words are based on those used in Hanique, Aalders, and Ernestus (2013), who constructed their pseudo-verbs by exchanging one or two letters in the

Table 2
Mean frequencies (Lg10CD) in Experiment 1, extracted from the SUBTLEX-NL database (Keuleers et al., 2010), and mean relatedness scores from the pretest that was performed (ratings were on a seven point scale on which 1 is completely unrelated to the target, and 7 highly related to the target) for the target (the stem + infinitival suffix) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Phonologically related (Ph), and Control (C) conditions. Standard deviations are given in parentheses.

	Example item	Frequency	Relatedness score
Target	*bieden* 'offer'	3.31 (0.49)	—
MS prime	*aanbieden* 'offer'	2.16 (0.63)	5.51 (0.70)
M prime	*verbieden* 'forbid'	2.30 (0.73)	1.91 (0.56)
Ph prime	*bespieden* 'spy'	1.58 (0.71)	1.19 (0.26)
C prime	*opjagen* 'hurry, rush'	1.97 (0.50)	1.12 (0.15)

stems of real verbs while preserving the phonotactic constraints and morphological structure of Dutch real verbs. Half of the fillers are complex words, and half of the fillers do not have a prefix, with the nonwords occurring with existing prefixes. All stimuli are presented in the infinitive form (stem + *en*), and all fillers are randomly combined to create prime-target pairs.

2.1.3. 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 normalized to a peak amplitude of 70 dB SPL. The task was implemented in PsychoPy2 (Peirce, 2007). Stimuli were presented auditorily to the participants through Sennheiser HD 280 PRO headphones.

2.1.4. Procedure

A continuous lexical decision task was used. The experiment consisted of four lists, with primes of the same target rotated according to a Latin Square design, such that each subject saw every target only once. The task had a random inter-stimulus interval (henceforth ISI) between 800 and 900 ms. The ISI was measured from the end of the sound file or participant response, whichever was later. Stimuli presentation was randomized throughout the experiment for each participant. The experiment consisted of 5 blocks with the possibility for a self-administered break after each block, and a practice trial of 8 items at the beginning of the experiment.

Participants were tested individually in a quiet room. Participants were instructed that they would hear existing and non-existing Dutch verbs, 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 for approximately 25 min per participant.

2.2. Results Experiment 1

2.2.1. Modeling

The data were analyzed 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. Trials with incorrect responses to primes or targets were discarded, which led to an exclusion of 31 data points out of a total of 1152 trials (36 targets * 32 participants). We follow Baayen and Milin (2010) and combine minimal a priori data trimming with post-fitting model criticism. 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 17 data points. The RT data were log-transformed, and removal of outliers was done for 5 individual subjects and 3 individual items for which Shapiro-Wilk's tests for normality showed non-Normal distributions, which led to the further removal of 26 data points. In total, a priori data trimming led to the exclusion of 43 observations, or 3.8%.

We analyzed effects on log-transformed RT (our dependent variable) with linear mixed-effects models, using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015, version 1.1-12) in the R environment (R Core Team, 2016, version 3.3.0). We first fit a model with a maximum random structure. Then, following recommendations by Bates, Kliegl, Vasishth, and Baayen (2015), a principle components analysis on the random-effects structures was performed, using the rePCA function in the RePsychLing package (Baayen, Bates, Kliegl, & Vasishth, 2015, version 0.0.4), to determine the optimal random structure supported by the data. This ensures that the model is not overly complex or underspecified in its random-effects structure. The analysis resulted in the inclusion of random intercepts for subjects, primes, and targets; random slopes did not improve model fit. The following main effects are included in the model: CONDITION (MS/M/Ph/Control), PRIMEPREFIX (whether the prime includes a separable or inseparable prefix), GROUP, ISI, TARGETFREQUENCY, PRIMEFREQUENCY, TARGETDURATION, PRIMERT, TRIAL, and TARGETNEIGHBORHOODDENSITY. CONDITION is treatment coded with the Control condition as the reference level. PRIMEPREFIX is sum-coded, and TARGETFREQUENCY, PRIMEFREQUENCY, TARGETDURATION, TRIAL, PRIMERT, ISI, and TARGETNEIGHBORHOODDENSITY are z-scored.

Model criticism was performed on the full model to identify overly influential outliers (Baayen & Milin, 2010). The model was refitted after excluding data points with absolute standardized residuals exceeding 2.5 standard deviations, which resulted in the exclusion of 23 observations (total removed outliers: 97, or 8.4%). The results of the final model after model criticism are presented here. *P*-values are determined using the package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2016); 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 (number of incorrect responses to targets and primes) per condition. RTs are measured from the onset of the sound file. Priming effect is the RT for the baseline Control condition minus the RT for the MS/M/Ph condition. Standard deviations are given in parentheses.

Condition	RT target	Priming effect	Inacc. responses
Control	922.56 (164.17)	*NA*	13
MS	834.08 (158.50)	88.48***	5
M	844.18 (161.06)	78.38***	5
Ph	904.81 (164.12)	17.75	8

2.2.2. Results

An overview of the results is provided in Table 3 and in Fig. 1. Table 3 gives the raw RT data, but note that the analyses are done on the log-transformed RT data (as indicated in Fig. 1). A model summary table is provided in Table 4. Additional models for which the reference level was adjusted can be found in the appendix.

The analysis of the log-transformed RT data revealed a significant facilitation in the MS condition ($\beta = -0.12$, $p < 0.001$) and in the M condition ($\beta = -0.10$, $p < 0.001$), compared to the baseline Control (C) condition. No priming was obtained in the Ph condition ($\beta = -0.02$, $p = 0.123$). In addition, and as expected for a lexical decision task, the model revealed a significant effect of TRIAL ($\beta = -0.04$, $p < 0.001$), showing that participants responded faster (lower RT) as the experiment progressed. The effect of TARGETDURATION was also significant ($\beta = 0.07$, $p < 0.001$), indicating that longer targets were recognized slower, since RT was calculated from the start of the sound file. Similarly, PRIMERT was significant ($\beta = 0.05$, $p < 0.001$), showing that how fast a participant responded to the

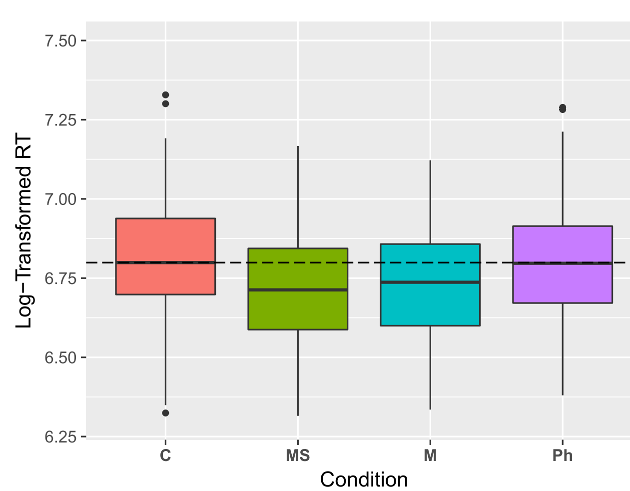

Fig. 1. Log-transformed response times in Experiment 1 for the Morphologically and Semantically related (MS), only Morphologically related (M), Phonologically related (Ph), and Control (C) conditions.

Table 4
Linear Mixed Effects Model summary for the analysis of RT data in Experiment 1, with the reference level of PRIMECONDITION set to the Control (C) condition.[a]

	Log-transformed RT		
Fixed Effects	*Estimate* (β)	*t-value*	*p-value*
(Intercept)	6.81	408.747	**<.001**
Prime Condition (C)			
M	−0.10	−8.150	**<.001**
MS	−0.12	−9.537	**<.001**
Ph	−0.02	−1.540	.123
Prime Prefix	0.02	2.634	**.008**
Trial Number	−0.04	−9.543	**<.001**
ISI	0.00	0.159	.874
Target Frequency	−0.02	−2.631	**.009**
Prime Frequency	0.02	3.515	**<.001**
Target Neighborhood Density	−0.01	−1.272	.203
Target Duration	0.07	9.831	**<.001**
Prime RT (log)	0.05	11.041	**<.001**
Random Effects	*N*	*Variance*	*St. dev*
Primes	143[b]	0.0003	0.018
Targets	36	0.0009	0.030
Subjects	32	0.0057	0.076
Residual		0.0157	0.126
N Datapoints	1055		

[a] Significant p-values ($p < 0.05$) are shown bold faced.
[b] Due to a coding error, the prime 'verbranden' occurred twice in the Control condition, but on different lists: once as the prime for *denken* in group 3, and once as the prime for *dragen* in group 4. This is the reason why the total number of individual primes is 143, rather than 144.

prime influenced RTs of the targets: in general, a participant responded slower to a target after they took longer to respond to the prime. Further main effects were found for TARGETFREQUENCY ($\beta = -0.02$, $p = 0.009$) and PRIMEFREQUENCY ($\beta = 0.02$, $p < 0.001$). This shows that participants responded faster to higher frequency targets than to lower frequency targets, but that they recognized a target slower after hearing a higher frequency prime. Furthermore, whether the prime includes a separable or inseparable prefix (PRIMEPREFIX) also turned out to be a significant predictor ($\beta = 0.02$, $p = 0.008$).

We performed a further planned comparison by resetting the reference level to the M condition. This allowed us to make additional comparisons between MS and M, and between Ph and M. The first comparison answers the question whether there is an additional effect of transparency on top of morphological effects; the second comparison if there is an additional effect of morphology on top of phonological effects. This separate model showed that there was no significant difference in the magnitude of priming between the MS and the M conditions ($\beta = -0.02$, $p = 0.169$), suggesting equal magnitudes of priming in morphologically related conditions regardless of semantic transparency. In addition, the Ph condition showed significantly longer RTs compared to the M condition ($\beta = 0.08$, $p < 0.001$).

2.3. Experiment 1 discussion

The goal of this experiment was to investigate what role morphological structure plays in the processing of Dutch complex verbs, while distinguishing morphological effects from semantic (transparency) and phonological effects. The results show that the primes in both the semantically transparent MS condition (*aanbieden* 'offer') and the semantically opaque M condition (*verbieden* 'forbid') significantly facilitate recognition of their stem (*bieden* 'offer'). The difference in priming effect between the MS and M conditions (88.48 and 78.38 ms, respectively) was not significant. These results fail to detect an effect of semantic transparency in Dutch complex verbs. In contrast to morphologically related prime-target pairs, purely phonologically related prime-target pairs (Ph; *bieden* 'offer' → *bespieden* 'spy') did not show a significant priming effect. The comparison between the M and Ph conditions shows that morphological effects are not just due to phonological overlap: the magnitude of priming is clearly and significantly distinct from the priming effects in the M condition.

These results are in line with the results for German prefixed verbs (Smolka et al., 2009; Smolka et al., 2014), in which it was also found that both morphologically and semantically related (*zubinden* 'tie') and morphologically related but semantically opaque (*entbinden* 'deliver') prefixed verbs prime their stem (*binden* 'bind'). The German experiments measured RTs to visually presented targets (in purely visual and cross-modal paradigms), while the present study used auditory targets. The results show that morphological priming in the absence of semantic transparency can be obtained for complex verbs not only in German, but also in Dutch, and not only in a visual or cross-modal priming paradigm, but also in an auditory-auditory paradigm.

Finally, the results show faster responses to verbs following inseparable prefixed verbs than following separable prefixed verbs. A similar finding is reported in Smolka et al. (2019) for German prefixed verbs. The authors suggest that this difference may result from a frequency effect because the inseparable prefixed verbs used in their study were generally more frequent than the separable prefixed verbs used. This is, prima facie, also the case for the stimuli in our study: inseparable prefixed verbs have a slightly higher frequency (mean = 2.10, sd = 0.76) than separable prefixed verbs (mean = 1.82, sd = 0.74). However, as pointed out to us by a reviewer, frequencies for separable prefixed verbs are not reliable, as they do not include the counts of the cases in which the verb and prefix are separated. The true frequency of the separable prefixed verbs may therefore be higher than what is standardly reported. While our experiment was not designed to investigate differences between separable and inseparable prefixed verbs, we note that it is possible that the difference is caused by the separability of the prefix. As pointed out by Schreuder (1990), what a finite verb form means may remain unclear until the whole utterance has been processed in the case of separable prefixed verbs, since the prefix is stranded at the end of the sentence. Therefore, speakers of Dutch (and German) might have learned that early commitment to the meaning of these verbs is not favorable. This could conceivably have a general effect on the target recognition in a primed lexical decision experiment. Of course, since in our stimuli the prefix occurs before the stem, an account based on unfavorable early commitment would require additional elaboration in order to predict the observed pattern.

In sum, the results of this experiment show that the semantically opaque M verbs significantly facilitate their stem. This suggests that semantic relatedness is not a precondition for the occurrence of morphological priming in Dutch prefixed verbs. In order to further investigate the (lack of) semantic effects, we include a Semantic condition in our next experiment (e.g., *bieden* 'offer' → *verlenen* 'give, grant') and manipulate the number of intervening items between prime and target.

3. Experiment 2

Our second experiment aims to further control for semantic effects in two ways. First, we include a Semantic condition (S) in which the primes and targets are semantically, but not morphologically or phonologically related to each other. These primes typically form synonyms of the targets (such as the prime *aanschouwen* 'see, watch' for the target *kijken* 'look, watch'), but in some cases the prime is not a synonym but still highly related in meaning to the target. All S primes are prefixed verbs. The addition of this condition allows us to investigate the extent to which the priming effects in the MS condition might be due to semantic relatedness. Moreover, the S condition allows us to rule out the possibility that the priming effects in the M condition are due to semantic priming via a semantically transparent activation of the meaning of the stem in M. Our participants might parse the semantically opaque words as having a semantically transparent meaning, even though we constructed our M condition in a way that, in principle, excludes the possibility of a transparent secondary meaning for the M stimuli (in contrast to the verbs in Zwitserlood et al., 2005 which are ambiguous between an opaque and a transparent sense as part of the experimental design). If the priming effects we find for M are due to our participants decomposing the M condition based on a (non-existing) transparent meaning of the prefix and stem, we expect to find priming in M that is similar to S.

Second, in case we find no difference in priming effects for MS, M, and S at an immediate distance, we include non-immediate priming as a tool to track the time-course with which different types of information (semantic/morphological) become available during word recognition and lexical access. In a non-immediate priming experiment, several words may intervene between the prime and its target, thereby prolonging the time interval between prime and target. Previous priming studies have shown that semantic priming effects decay more quickly over time than morphological effects (visual modality: Bentin & Feldman, 1990; Feldman, 2000, i.a.; auditory modality: Kouider & Dupoux, 2009; Marslen-Wilson & Tyler, 1998). Therefore, if our M, MS, and S conditions show similar priming effects at an immediate distance (and to the extent that morphological and semantic factors indeed exhibit different patterns over time), a long-distance priming paradigm forms a valuable tool to tease apart the semantic and morphological contributions to the word recognition process. Since semantic priming effects decay more quickly over time than morphological effects, we predict that, if all conditions induce priming effects at an immediate distance (0-lag), we will see a clear difference between the conditions at a distance (5-lag) with the MS (priming not only semantically but also morphologically) and M verbs facilitating recognition of the target to a greater extent than the S verbs.

3.1. Method Experiment 2

3.1.1. Participants

Participants were 40 adult native speakers of Dutch, most of whom were students or recent alumni of the University of Amsterdam (mean age = 28.81; sd = 11.35). All were raised monolingual, and reported having no reading, hearing, or other language disorders. Participants were paid a small fee (5 euros) for their participation.

3.1.2. Materials

This experiment includes the M (morphologically related, semantically opaque) and MS (morphologically and semantically related) conditions that were included in Experiment 1. Since the Phonological effects in Experiment 1 did not reach significance and were clearly distinct from the morphological effects, we replace the Ph (phonologically related) condition with a Semantic (S) condition, in which the prime and target are semantically related, but not phonologically or morphologically. Finally, we again include a Control (C) condition of prime-target pairs that are neither phonologically, semantically, nor morphologically related to their base. The conditions and example items are given in Table 5; all items can be found in the appendix.

In total, the experiment includes 40 base verbs which function as the targets. The base verbs are the same as were used in Experiment 1, with the addition of four verbs (*keren, komen, roeren, spreken*) and their primes, as well as the primes for the S condition. Furthermore, we changed some items in the other conditions because they had similar stems as the added items. Every subject heard 10 items per condition, half of which are presented at an immediate distance, and half at a 5-item-lag between prime and target.

As with Experiment 1, semantic relatedness scores were established by a pre-test, the details of which can be found in the appendix. Table 6 provides prime and target mean frequencies and mean semantic relatedness scores per condition.

Experiment 2 includes 180 filler pairs, so that the critical items make up 18.2% of all items. We included fewer filler items in this experiment than we did in Experiment 1 because of the addition of the distance manipulation, due to which participants are less likely to become aware of the critical manipulation. Only half of the targets are presented immediately after their prime, which amounts to 9.09% of all items. Of the 360 filler items in total, 140 were real words and 220 were non-words. Half of all fillers are complex words, and half of the fillers do not have a prefix (the non-words occur with existing prefixes). The fillers are selected from the fillers that were used in Experiment 1, and are randomly combined to create prime-target pairs.

Table 5
Conditions and example critical items in Experiment 2, for the target (the stem + infinitival suffix) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Semantically related (S), and Control (C) conditions. Half of the items are presented at an immediate distance, and half at a distance of 5 intervening items between prime and target.

Target	MS prime	M prime	S prime	C prime
bieden	*aanbieden*	*verbieden*	*verlenen*	*opjagen*
'offer'	'offer'	'forbid'	'give, grant'	'hurry, rush'
schieten	*beschieten*	*opschieten*	*afvuren*	*bezoeken*
'shoot'	'fire on/at'	'hurry up'	'fire'	'visit'
werpen	*afwerpen*	*ontwerpen*	*weggooien*	*uitdraaien*
'throw'	'throw off'	'design'	'throw away'	'print out'

Table 6
Mean frequencies (Lg10CD) in Experiment 2, extracted from the SUBTLEX-NL database (Keuleers et al., 2010), and mean relatedness scores from the pretest that was performed (ratings were on a seven point scale on which 1 is completely unrelated to the target, and 7 highly related to the target) for the target (the stem + infinitival suffix) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Semantically related (S), and Control (C) conditions. Standard deviations are given in parentheses.

	Example item	Frequency	Relatedness score
Target	*bieden* 'offer'	3.29 (0.54)	—
MS prime	*aanbieden* 'offer'	2.18 (0.63)	5.55 (0.64)
M prime	*verbieden* 'forbid'	2.25 (0.75)	1.89 (0.56)
S prime	*verlenen* 'give, grant'	2.06 (0.86)	5.45 (0.77)
C prime	*opjagen* 'hurry, rush'	1.93 (0.52)	1.12 (0.52)

3.1.3. Apparatus

The method of recording, implementation of the task, and presentation of the stimuli are identical to Experiment 1.

3.1.4. Procedure

As in Experiment 1, a continuous lexical decision task was used. Stimuli were presented at an immediate distance (0-lag) and at a distance of five intervening items between prime and target (5-lag). Lexical decisions were made to all items, including the items intervening between primes and targets. The experiment consisted of eight lists, with primes of the same target rotated according to a Latin Square design, such that each subject saw every target only once. Distance was manipulated between-subjects, such that different participants saw primes at either 0- or 5-lags. Participants could take two self-administered breaks during the experiment. The experiment included a practice trial of 8 items at the beginning of the experiment. The task had a random ISI between 600 and 800 ms, and lasted for approximately 15 min. The ISI was slightly reduced compared to Experiment 1 to make the task shorter, and consequently less taxing for participants. The rest of the procedure was the same as in Experiment 1.

3.2. Results Experiment 2

3.2.1. Modeling

The modeling for Experiment 2 was similar to Experiment 1. Discarding of incorrect responses to primes and targets led to an exclusion of 99 out of 1600 critical items. Minimal a priori data trimming (Baayen & Milin, 2010) led to a further exclusion of 28 data points for targets with outlier RTs (<100 ms and >2000 ms), as well as all targets for which the prime had an outlier RT. The RT data were log-transformed, and further outlier removal was done for 10 individual subjects and 1 item for which Shapiro-Wilk's tests for normality showed non-Normal distributions (leading to the further removal of 19 data points). In total, a priori data trimming led to an exclusion 47 observations, or 3.13% of the data after exclusion of inaccurate responses. The effects on log-transformed RT are analyzed with linear mixed-effects models (Bates et al., 2015). Random effect optimization (Bates et al., 2015) indicated that the participant-related and target-related variance component for the MS condition significantly improved model fit, while the other factors for condition did not. This resulted in a random effects structure with by-subject and by-target slopes for the MS condition, as well as random intercepts for subjects, primes, and targets.

The following main effects are included in the model: PRIMECONDITION (MS/M/Ph/C), DISTANCE (0-lag, 5-lag), and their interaction, PRIMEPREFIX (whether the prime includes a separable or inseparable prefix), TRIAL, ISI, TARGETFREQUENCY, PRIMEFREQUENCY, TARGETNEIGHBORHOODDENSITY (PTAN), and TARGETDURATION. PRIMECONDITION is treatment coded with the Control condition as the reference level, DISTANCE is treatment coded with 0-lag as the reference level, and PRIMEPREFIX is sum-coded. TRIAL, ISI, TARGETFREQUENCY, PRIMEFREQUENCY, TARGETNEIGHBORHOODDENSITY, and TARGETDURATION are z-scored. As for Experiment 1, model criticism was performed on the full model to identify overly influential outliers (Baayen & Milin, 2010), which resulted in the exclusion of 29 observations, after which the model was refitted.

3.2.2. Results

Table 7 provides an overview of the raw RTs and error rates for all four conditions at a 0-lag and at a 5-lag distance. Figs. 2 and 3 give the mean response times (log ms) in all four conditions at both lags.

At 0-lag, the analysis of the log-transformed RT data revealed a significant priming effect for the MS condition ($\beta = -0.06, p < 0.001$) and for the M condition ($\beta = -0.06$, $p < 0.001$), compared to the Control condition. No significant difference was found between the Semantic condition and the Control condition ($\beta = -0.01, p = 0.365$). In addition, and as expected for a lexical decision task, the model revealed a significant effect of TRIAL ($\beta = -0.02$, $p = 0.002$), showing that participants responded faster as the experiment progressed, and of TARGETDURATION ($\beta = 0.06$, $p < 0.001$), indicating that longer targets were recognized slower since RT was calculated from the start of the sound file. In contrast to the results of Experiment 1, PRIMEPREFIX did not show a significant effect ($p = 0.842$). A summary of this model is provided in Table 8. Additional models can be found in the appendix.

Further planned pairwise comparisons of PRIMECONDITION at a 0-lag were obtained by setting the reference level to MS using the same model, while keeping the reference level for DISTANCE set to 0-lag. This allowed us to see if there is an additional effect of morphology on top of semantics (MS-S), and if there is an additional effect of semantic transparency (MS-M), at a 0-lag.

Table 7
Mean response times (RTs) to the targets (in ms), priming effects (in ms), and error rates (number of incorrect responses to targets and primes) in Experiment 2, per condition and per lag (0 and 5). RTs are measured from the onset of the sound file. Priming effect is the RT for the baseline Control condition minus the RT for the MS/M/S condition. Standard deviations are given in parentheses.

Condition	Lag	RT target	Priming effect	Inacc. responses
MS	0	913.53 (168.62)	54.10***	4
M	0	906.47 (159.25)	61.16***	4
S	0	950.63 (161.49)	17.00	14
Control	0	967.63 (160.74)	—	12
MS	5	981.48 (180.11)	−14.35	15
M	5	965.69 (165.18)	1.45	13
S	5	977.55 (163.50)	−10.41	20
Control	5	967.13 (168.39)	—	17

The model showed that, at a 0-lag, there was no significant difference between MS and M ($p = 0.708$), while there was a significant difference between MS and S ($\beta = 0.04$, $p = 0.002$).

With respect to the different lags used, the two-way interaction between PRIMECONDITION and DISTANCE in the first model indicates that the priming effect (comparing the critical condition to C) for MS at a 0-lag is significantly larger compared to the priming effect for MS at a 5-lag distance ($\beta = 0.06$, $p < 0.001$), and the same holds for the priming effect for M at a 0-lag and at a 5-lag distance ($\beta = 0.05, p = 0.002$), while no difference was found for S ($p = 0.156$). The interaction in the second model furthermore indicates that the decay for MS between the 0-lag and 5-lag does not significantly differ from the decay for the M condition ($p = 0.597$).

Finally, to take a further look at the effects at a 5-lag, we fit a model with the same model structure, in which we set the reference level of DISTANCE to 5-lag and the reference level of PRIMECONDITION to the C condition. This reveals that none of the effects for PRIMECONDITION were significant at a 5-lag distance (MS: $p = 0.612$; M: $p = 0.575$; S: $p = 0.274$).

3.3. Experiment 2 discussion

The goal of our second experiment was to further investigate to what extent semantic relatedness plays a role in the processing of morphologically complex words. At a 0-lag, the results replicate the results in Experiment 1, in that the primes in both the semantically transparent MS condition (*aanbieden* 'offer') and the semantically opaque M condition (*verbieden* 'forbid') significantly facilitate recognition of their stem (*bieden* 'offer'), with no difference between the amount of facilitation in both conditions. In contrast to morphological priming, purely semantically related prime-target pairs (*verlenen* 'give, grant' → *bieden* 'offer') did not show a significant priming effect at a 0-lag. The comparison between the MS and S conditions shows that the morphological effect that we see in the MS condition is larger than we would expect from mere semantic overlap. This allows us to make a stronger inference regarding the M condition as well, as the absence of semantic effects shows that the priming in the M condition is not due to an attempt of our participants to give a semantically transparent parse to the complex verbs in this condition.

While we expected to find a gradual drop-off in the priming effects, instead, none of the effects reach significance at a 5-lag. It is likely that the lag we used (5 intervening items between prime and target) was too large to see a gradual drop-off. This is surprising considering earlier results with long-distance priming in the auditory domain by Marslen-Wilson and Tyler (1998) (12 intervening items), Kouider and Dupoux (2009) (18 to 144 intervening items), and Wilder et al. (2019) (0, 1, and 5 intervening items). However, these studies used shorter (often monosyllabic) words, whereas our words were two or three syllables in length, and were therefore longer. We suspect that using a lag of one or two intervening items might have shown the drop-off in the facilitation effects, while at a 5-lag all effects have already disappeared.

Moreover, it is surprising that we did not find significant semantic effects at a 0-lag. The rationale of including prime-target pairs that are presented at a 5-lag, was that we expected to see semantic effects at a 0-lag. However, Smolka et al. (2014) report a similar finding for verb-verb pairs. In their Experiment 1 (purely visual) and Experiment 2 (cross-modal), the S condition also did not show significant facilitation (and similar findings are reported in Smolka et al., 2009). In their Experiment 3 (purely visual), Smolka et al. (2014) added semantically related 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, now the semantically related verbs (as well as the nouns) showed significant facilitation, which was equally strong as the morphologically related (MS and M) conditions. The authors argue that the top-down procedure participants used to complete the task is, in fact, sensitive to detecting semantic influences, and that the semantically related verbs can be primed under conditions that promote semantic priming across mixed word classes.

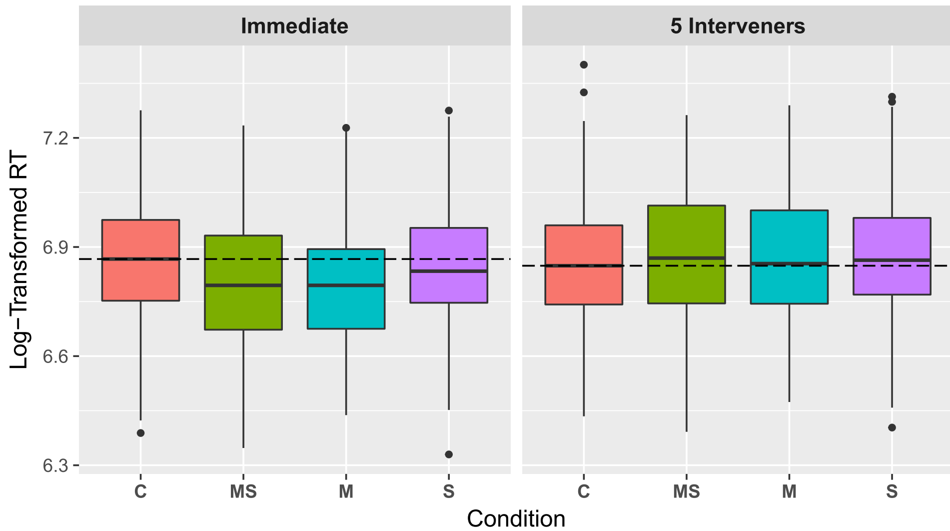

Fig. 2. Log-transformed RTs in Experiment 2 (after data trimming) for the Morphologically and Semantically related (MS), only Morphologically related (M), Semantically related (S), and Control (C) conditions, over a distance of zero intervening items (left), and five intervening items (right) between prime and target.

Moreover, while behavioral data are inconsistent when it comes to verb-verb associative priming, electrophysiological data indicate strong semantic priming effects in terms of N400 modulations (Smolka, Khader, Wiese, Zwitserlood, & Rösler, 2013; Smolka et al., 2015). It is important to note that the lack of semantic facilitation stresses the effect of morphological relatedness even more: the lack of semantic facilitation in the S condition clearly demonstrates that the strong morphological facilitation effects in the MS condition were not due to meaning overlap between prime and target.

Finally, when we compare the magnitude of priming effects in the MS and M conditions between Experiment 1 and Experiment 2 at immediate distance, we see numerically slightly larger effects in Experiment 1 (Experiment 1: 88.48 and 78.38 ms, Experiment 2: 54.10 and 61.16 ms). The most likely explanation for this difference is the shorter ISI that was used in Experiment 2 (Experiment 1: 800–900 ms; Experiment 2: 600–800 ms).

4. General Discussion

The experiments presented in this paper investigate the processing of morphologically complex verbs in Dutch. They address the specific question of what effects the semantic opacity of a prefixed verb has on its relation to its stem. The results of the two experiments show equal and robust priming in the semantically transparent MS and the semantically opaque M conditions (at a 0-lag), while no significant priming effects were found for only phonologically related items (Experiment 1) or only semantically related items (Experiment 2). The results for the Semantic and Phonological conditions indicate that the effects in the MS and M conditions cannot be attributed to mere semantic or phonological overlap.

Our results are in line with the findings for German by Smolka et al. (2009, 2014, 2015, 2019). They also extend the finding of morphological processing independent of semantic transparency reported in De Grauwe et al. (2019). Importantly, in comparison to De Grauwe et al. (2019), the present experiments employ a more powerful within-items rather than between-items design, and, crucially, our experiments include phonological and semantic controls that allowed us to rule out the possibility that facilitation was the result of form and/or meaning overlap. Having established that opaque complex words are truly related to their embedded stem, we leave it for future research to investigate further questions regarding the temporal activation of meaning representations for opaque versus transparent complex words. This relates to the contrasts in semantic/associative priming between Dutch opaque and transparent words that have been reported (De

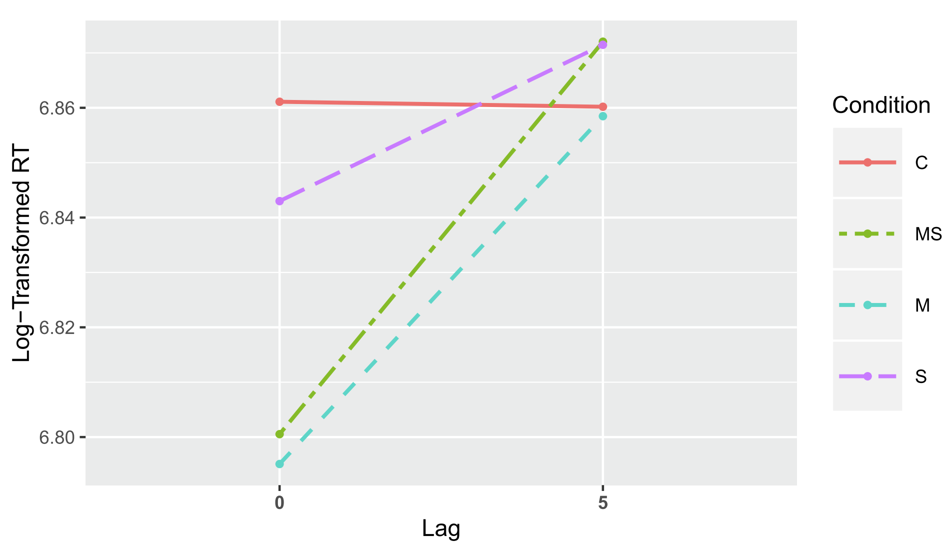

Fig. 3. Log response times in Experiment 2 (after data trimming) for Morphologically and Semantically related (MS), only Morphologically related (M), Semantically related (S), and Control (C) conditions, at the two lags used between prime and target.

Table 8
Linear Mixed Effects Model summary for the analysis of RT data in Experiment 2, with the reference level of PRIMECONDITION set to the C condition, and the reference level of DISTANCE set to 0-lag.[a]

	Log-transformed RT		
Fixed Effects	*Estimate (β)*	*t-value*	*p-value*
(Intercept)	6.86	363.411	**<.001**
Prime Condition (C)			
MS	−0.06	−3.848	**<.001**
M	−0.06	−4.981	**<.001**
S	−0.01	−0.906	.365
Distance 5-lag	0.00	0.188	.851
Prime Prefix	0.00	0.199	.842
Trial Number	−0.02	−3.165	**.002**
ISI	0.00	0.560	.576
Target Frequency	−0.01	−1.910	.056
Prime Frequency	0.00	1.111	.267
Target Neighborhood Density	−0.01	−1.948	.051
Target Duration	0.06	9.016	**<.001**
Prime Condition MS: Distance 5-lag	0.06	3.627	**<.001**
Prime Condition M: Distance 5-lag	0.05	3.100	**.002**
Prime Condition S: Distance 5-lag	0.03	1.419	.156
Random Effects	*N*	*Variance*	*St. dev*
Prime Intercept	160	0.0000	0.000
Targets	40		
Intercept		0.0016	0.040
MS slope		0.0021	0.046
Subjects	40		
Intercept		0.0095	0.098
MS slope		0.0003	0.016
Residual		0.0137	0.117
N Datapoints	1425		

[a] Significant *p*-values ($p < 0.05$) are shown bold faced.

Grauwe et al., 2019; Zwitserlood et al., 2005). Investigating the activation of morphological representations versus the activation of semantic representations (and their temporal dynamics) may also shed further light on reported early whole-word effects (Kuperman et al., 2009, 2010; Schreuder et al., 2003).

Also noteworthy is the fact that the experiments in the present study were conducted in the intra-modal auditory modality. Our results, therefore, show that morphological effects for truly morphologically derived words are not restricted to the visual recognition of target words, but extend to auditory target recognition as well. This rules out the possibility that apparent effects of morphological relatedness are due to properties of the orthographic system (cf. Rastle et al., 2004; Rastle & Davis, 2008). In addition, and as argued in Section 1.3, the visual and auditory modalities might very well provide different windows on phenomena of interest; thus, the consistency between earlier visual and cross-modal decomposition effects in German and the current intra-modal auditory effects in Dutch is of interest in its own right.

4.1. Implications for models of the mental lexicon

A long-standing idea in both linguistic and psycholinguistic theories is that irregular word formation processes (that is, irregular morphophonological forms and non-predictable meanings) are represented differently from regular word formation processes (that is, morphophonologically predictable and semantically transparent). The *lexicalist* position, adopted by various linguistic theories, is particularly relevant in this respect (for a review see Carstairs-McCarthy, 1992). Different lexicalist theories take a wide range of positions on a number of important matters; however, they tend to agree that while morphological rules play some role in regular word formation processes, irregular words that appear to be complex are represented differently. In many theories, they must be listed as unanalyzable wholes in the lexicon. A strong current emerging in more experimentally-oriented approaches also takes a similar stance on this issue, as discussed below.

Our results are incompatible with theories that make semantic overlap a precondition of morphological relatedness, and favor theories that do not have this property. In the sections below, we review some of the most important positions that are implicated in this divide between theories. However, before looking at the implications for particular models, some comments are in order about the scope of the argument that is being developed; in particular, concerning the question of the role of meaning overlap in morphological relatedness effects on the one hand, versus the question of morphological decomposition on the other. For our purposes, what is most relevant about such theories is not their stance on whether a word is *decomposed* into constituent morphemes or not; rather, it is the question of whether regular and irregular formations are *morphologically related* to their stems in the same way. Questions about decomposition and relatedness are often closely connected, but they can be disentangled from each other. With respect to the materials used in this paper, it could be asked both (i) whether e.g., *verbieden* ('forbid') is decomposed into a prefix *ver-* and a part *bieden*, and (ii) whether *bieden* in *verbieden* is the same morpheme that occurs as free-standing *bieden*.

While the decomposition question arises in the case of verbs like *verbieden*, there are clear reasons to think that at least half of our prefixed verbs must be represented as separate pieces. In particular, separable prefixes, like *aan* in *aanbreken* ('open, begin; lit. to-break'), may be separated from the verb stem by, in principle, any number of clauses due to the 'verb second' effect in Dutch main clauses. For instance, the separable prefix in the verb *op-staan* ('get up') in *Zij* **staan** *morgen wat vroeger* **op** ('They get up somewhat earlier tomorrow') appears sentence finally and is separated from the finite verb (cf. Den Besten, 1983; Schreuder, 1990). About half of our stimuli occur with separable prefixes, such that the question of decomposing a word into a stem and an affix is not a central concern: they can be separated syntactically, and are clearly two pieces.

For the reasons outlined in the introduction, our main focus in this paper is on the question of morphological relatedness: we find evidence for relatedness between prefixed verbs and their stems that is independent of semantic overlap, and not due to phonological similarity. How such relatedness effects are to be accounted for is a complex question. As noted above, it is evident that our results are not compatible with models which assume that semantic transparency is a precondition for relatedness. The models that our results are compatible with, Full-Decomposition models as well as versions of a Discriminative Learning model, share the idea that semantic overlap is not required for relatedness but differ along a number of other interesting dimensions, including basic architectural assumptions. For this reason, we treat them separately in Sections 4.1.2 and 4.1.3, respectively. General conclusions are presented in Section 4.2.

4.1.1. Semantic relatedness as a precondition for morphological effects

Many models of the mental lexicon view semantic overlap as a precondition for relatedness. These models do not predict morphological effects in the absence of semantic transparency, and are therefore incompatible with the present findings for Dutch.

For instance, according to a Supralexical model (Giraudo & Grainger, 2003, 2001; Voga & Giraudo, 2009), there is an initial stage of whole-word processing followed by a later stage of decomposition in which morphemes receive activation from the whole-word representation. The supralexical account predicts that morphological priming only occurs for semantically transparent prime-target pairs, since only these share representations at the morphemic level (Diependaele et al., 2005).

Similarly, parallel Dual-Route models are not compatible with our findings. Dual-Route models propose that both decomposition and whole-word access can take place, and that the route taken depends on the type of word that is being accessed. The Morphological Race Model (Frauenfelder & Schreuder, 1992, see also Baayen et al., 1997), for instance, posits that both ways of accessing a complex word, through decomposition and through whole-word access, are in competition. The winner of the 'race' is determined mainly by the frequency and the phonological and semantic transparency of the word to be accessed. Transparent low frequency words have the highest chance of winning the 'decomposition route', while high frequency words and semantically opaque words are accessed through whole-word lexical entries. Therefore, semantically opaque words as the ones used in the present study are not expected to significantly prime their stem under this account, since these words are most likely to be accessed through their whole-word forms.

Our findings are also incompatible with parallel-distributed connectionist models (PDP: Gonnerman et al., 2007), which argue that morphemic structure emerges when stable sub-patterns develop in response to the consistent co-occurrence of orthographic, phonological and semantic information (e.g., Plaut & Gonnerman, 2000; Raveh, 2002; Seidenberg & Gonnerman, 2000). Morphological structure in such models has no independent status. Rather, putatively morphological effects emerge from a learned mapping between orthography, phonology, and semantics. Morphological effects are therefore predicted to occur only for semantically compositional words (stemming from the joint contribution of formal and semantic similarity), and the strength of morphological effects should diminish as the semantic similarity between the morphologically related words decreases.

4.1.2. Full-decomposition

One type of model of the mental lexicon that can offer a straightforward explanation for our findings is centered on morphological decomposition, and the idea that complex words are represented such that there is representation and processing of morphology that is independent of semantics and phonology (Smolka et al., 2014, 2019; Stockall & Marantz, 2006; Taft & Forster, 1975; Taft, 1979; Taft, 2004; Fruchter & Marantz, 2015, i.a.). The most familiar versions of such models, often termed *Full-Decomposition*, adopt the further assumption that morphemes are discrete objects in memory. When fleshed out, some other processing stages in addition to decomposition are identified as well. For example, Taft (1979, 2004) argues that complex visual words are recognized via a multi-stage process of decomposition into their component morphemes, look-up of the lexical entries of the morphemes (the activation of morphemes as objects in memory), and recombination of the separate morphemes into the complex form (see also Fruchter & Marantz, 2015; Taft & Forster, 1975; Wilder et al., 2019).

Full-Decomposition models predict relatedness effects between *aanbieden* ('offer')/ *verbieden* ('forbid') and *bieden* ('offer') because these complex words are decomposed so that they contain *bieden*. In other words, *bieden* (or perhaps *bied* if we abstract away from the infinitival morpheme) has a single representation in memory that is activated regardless of whether the word form it appears in has a transparent or opaque meaning. Morphological *priming* in a Full-Decomposition model is, therefore, priming via reactivation (Stockall & Marantz, 2006). The prime *verbieden* activates the morpheme *bieden*, which remains active and is therefore above its resting level of activation when the target *bieden* is encountered. Since both prime and target contain the same morpheme, regardless of semantic transparency, recognition is predicted to be facilitated. The key notion for Full-Decomposition models is the *independence* of morphological representation from the semantics and phonology of a particular word in which a morpheme might appear.

What it means for morphology to be independently represented looks somewhat different for functional versus lexical morphemes. Beginning with the former, a useful place to start is with divergences from the simplest 'one-form, one-meaning' scenario. The well-studied past-tense morphology of English provides suitable examples. While the default past tense form is (orthographic) *-ed*, past tense is also expressed with *-t* (as in *bend/bent*), with no overt realization (*hit/hit*), and with various combinations of what look like morphemes, plus stem changes (*tell/told; bring/brought*). Whatever one says about the analysis of these different relations, all of the right-hand members of these pairs have the same syntactic and semantic distribution: they all occur in past tense contexts. Their difference in form suggests an abstraction like [+past] that exists independent of the particular phonological changes that express it. The same considerations apply to words that do not share a common meaning. While past tense might be a typical meaning for the forms in question, they also appear in other contexts, such as irrealis (*I wish I worked at a tire factory*), sequence of tense (*Mary said that she was in the office*), politeness (*Did you want fries with that?*), and many others. The appearance of past tense forms that abstract away from a particular meaning and sound, is therefore taken to correspond to a feature like [+past], that is represented independent of form and meaning (for additional discussion, see Bacovcin et al., 2017; Goodwin Davies, 2018; Goodwin Davies et al., submitted for publication; Marantz, 2013).

While the example of [+past] is about affixes, the same holds for the stems in irregular past tense verbs: verbs like *leave/left* and *bring/brought* can be decomposed into a shared part, that is the stem, regardless of phonological idiosyncracies (see Stockall & Marantz, 2006). Similarly, for the meaning side, words like *understand* and *stand* share a stem, regardless of semantic idiosyncracies. The same sorts of considerations have also been applied in the study of transparency and opacity in compounds; see for instance Fiorentino and Poeppel (2007) for a representative view.

In summary, a Full-Decomposition model is able to explain the results reported here by treating words as sharing the same parts. Because these parts have an existence that is independent of (though crucially related to) semantics and phonology, relatedness effects arise even when there is no overlap in meaning between the prime and the target. Regarding the scope of this model's predictions, we note that a Full-Decomposition model is not committed to *exactly* the same level of facilitation for opaque and transparent pairs at every stage of processing; semantic inhibition of the stem in opaque words is expected to occur at some point in the process of word recognition. Further investigation using the types of stimuli employed in this study might be able to disentangle these different processing stages, and identify differences between the processing of opaque and transparent complex words.

4.1.3. Discriminative learning

As pointed out to us by a reviewer, approaches employing different types of discriminative learning (henceforth DL) also appear to predict relatedness effects independent of semantic overlap. Baayen et al. (2011) propose a computational model for morphological processing in visual word recognition, based on naive discriminative learning (NDL). In this model, orthographic representations of letter unigrams and bigrams ('cues') are mapped directly onto semantic representations ('outcomes'; such as meanings of words, inflectional meanings, and affixal meanings), without the intervention of form representations of morphemes or whole words.

Baayen et al. (2011) show that an NDL model is able to produce the morpho-orthographic decomposition effects in Rastle et al. (2004) without a "morpho-orthographic parsing component". The model obtained significant and equal effects for transparent (*employer* → *employ*) and pseudo-derived (*archer* → *arch*) words. Because this NDL model explicitly represents form/meaning associations, it is worth reflecting on why it produces relatedness effects (interpreted as priming) between words that do not share a meaning.

Baayen et al. (2011) begin their explanation with the observation that pseudo-derived words like *early*, *fleeting*, *fruitless*, and *archer* vary in the extent to which the suffix (and sometimes the stem) conveys its regular meaning. For *archer*, for example, it is argued that it is still transparently related to the meaning of the suffix that marks the complex noun an agent noun, even if the base is no longer synchronically related to the complex word. The associations between the letter cues and suffix meanings then emerge because for the majority of pseudo-derived items, the suffix is "fully functional in the meaning of the complex word" (Baayen et al., 2011, p. 466). Against this background, it is suggested that the equal effects for transparent and pseudo-derived items arise because the orthographic representations for suffixes have become associated with suffix meanings also in pseudo-derived items.

Part of this is clear: if words like *archer* are agentive nouns, and end in *-er* like many other transparent agent nouns like *teacher* do, then the associative learner will form an association between *-er* and that kind of nominal meaning. However, it remains unclear in the discussion of the NDL model why *archer* would have a connection with *arch*, which has neither the agent noun semantics, nor ends in *-er*. That is, learning that *-er* is associated with a meaning like 'agent noun' is one thing, and might associate *archer* with *teacher*; but it is not clear why (aside from string overlap) *archer* and *arch* are associated with each other in this model.[2]

It is important to further note that the data modeled (from Rastle et al., 2004) are pseudo-derived. Therefore, as outlined in the Introduction, they differ in important ways from the opaque (M) condition that is employed in our paper. Subsequent models (Milin et al., 2017; Baayen et al., 2019, i.a.) change different aspects of the discriminative learner, but, crucially, these papers do not examine opaque versus transparent pairs like the ones employed in our experiments.

A recent manuscript by Baayen and Smolka (2019) does examine this for German opaque and transparent prefixed verbs, and models the German stem priming patterns using NDL. If this finding translates to Dutch, a point worth investigating in future work is why the NDL model produces this effect, if meanings are an important part of how associations are formed. It is conceivable that what the model is associating is formal strings– that is, overlapping trigram sequences. This possibility is not ruled out by the Phonological condition used in our experiment: our prefixed verbs and their stems overlap in both MS (*aanbieden* → *bieden*) and M (*verbieden* → *bieden*) conditions, but not in our Ph condition (*bespieden* → *bieden*), which was tailored to the requirements of auditory presentation (ruling out facilitation due to rhyme prime), and not directed at string overlap. One way to probe questions of this type would be to look directly at experimental evidence on the processing of string-overlapping words such as *hamster* →*ham* or homophones like *bank* → *bank*, and see how the model's behavior on these stimuli compares to prefixed verbs in our M condition.

Overall, it remains to be seen precisely what types of associations a DL model produces in our M and MS pairs. These, along with the question of how to distinguish the predictions of Full-Decomposition and learning models that produce M and MS facilitation, are important tasks for future work.

4.2. Conclusions

The main finding of this paper is that semantically opaque prefixed words in Dutch produce morphological priming effects. These findings have important implications for models of the mental lexicon, which can be split along the dimension of whether semantic overlap is a precondition for relatedness. These results are compatible with Full-Decomposition as well as Discriminative Learning models. As noted above, further work is required to determine what might distinguish the predictions of these different models. As far as this goes, there are two further points to be made.

A first point concerns modality. There appear to be differences in morphological priming effects between visual and auditory presentation (Wilder et al., 2019), suggesting that the left-to-right nature of auditorily presented words should be taken into account in explaining the types of effects we discuss here. This is something to bear in mind in making decompositional and DL models more commensurable. For example, a DL model that predicts effects like those reported here, but which is based on orthographic representations, might be looking at something that differs in important ways from the effects that are produced in auditory processing. These differences make a direct comparison between different models difficult; along these lines, see Baayen et al. (2019) for a move towards modelling auditory comprehension.

A second point concerns the most important finding of this paper: morphological relatedness effects do not require semantic overlap. Although we have spent some time above talking about the different ways in which Full-Decomposition and Discriminative Learning models might produce this effect, the finding in itself must be emphasized. From one point of view, the fact that, despite the different starting assumptions, both Full-Decompositional and Discriminative Learning models posit that there might be relatedness effects that are independent of phonological and semantic overlap is significant. This suggests a striking point of convergence that goes beyond the different starting assumptions and explanatory aims of these approaches.

Data availability

Data and analyses are available at https://doi.org/10.17632/c7rcjsbyhh.1.

Funding

This work was supported by the National Institutes of Health Grant No. R01HD073258.

Consent

Written informed consent was obtained for experimentation with human subjects.

Declaration of Competing Interest

None.

Acknowledgements

Many thanks are due to Hezekiah Akiva Bacovcin, Jan Don, Kobey Shwayder, the members of ExpMorph, FMART and the Language Variation and Cognition Lab at Penn, the audiences at SLE, PLC and the Mental Lexicon for their feedback, and two reviewers for their helpful comments on previous versions of this manuscript. We thank Pienie Zwitserlood for sharing her stimuli with us, and Ava Irani for proofreading the manuscript.

Appendix A

A.1. Semantic relatedness pretest

To establish the semantic relatedness between primes and targets, a semantic relatedness pre-test was conducted with at least two candidate complex verbs for every target base verb. For both experiments, twelve 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'. The pretest was conducted through Qualtrics. For every target, multiple primes were included in the pretest, so that the semantically most/least related pairs could be selected as critical items. Targets for which it turned out that there was no appropriate prime in one or more of the conditions were excluded.

[2] Another question for the Baayen et al. (2011) model concerns what precisely is being modelled. The contrast between the results in masked versus overt priming paradigms with pseudo-derived items, which is often reported for English (see Section 1.1.1), is not addressed, but plays a prominent role in most attempts to understand these phenomena.

Criteria for including items as critical items in Experiment 1 were as follows: MS verbs needed to have a mean semantic score that was higher than 4, and M, Ph, and C verbs needed to have a mean score lower than 3 in order to be included in the critical items. This resulted in the 36 critical item stems (targets) and their complex verbs (primes) in the four different conditions that were used in this experiment. A one-way ANOVA was performed on mean semantic scores, which showed highly significant differences between conditions ($F(3,140) = 698.7$, $p < 0.001$). Post-hoc testing with Tukey's test shows that the MS and M conditions are significantly different ($p < 0.001$).

For Experiment 2, criteria for inclusion were identical to those for Experiment 1. In addition, S primes needed to have a mean semantic score that is higher than 4 (similar to MS primes). A one-way ANOVA was performed on mean semantic scores, which showed highly significant differences between conditions ($F(3,156) = 652.1$, $p < 0.001$). Post-hoc testing with Tukey's test shows that the MS and S conditions do not significantly differ ($p = 0.876$), while the semantic scores in the MS and M conditions are significantly different ($p < 0.001$).

Appendix B

B.1. Stimuli Experiment 1

See Table 9

Table 9
Stimuli in Experiment 1, for the target (the stem + infinitival suffix) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Phonologically related (Ph), and Control (C) conditions. For Ph prime-target pairs, the stem of the prime and the target rhyme: they only differ in their onset consonant or consonant cluster, while sharing the rhyme. In two cases (*houden* and *nemen*) we allowed a minimal difference in the coda as well, since no rhyming alternative could be found.

Target	MS prime	M prime	Ph prime	C prime
bieden	*aanbieden*	*verbieden*	*bespieden*	*opjagen*
'offer'	'offer'	'forbid'	'spie on'	'rush'
bijten	*afbijten*	*verbijten*	*verwijten*	*verhuren*
'bite'	'bite off'	'suppress'	'blame'	'lease'
blijven	*verblijven*	*afblijven*	*verdrijven*	*opmeten*
'stay'	'stay'	'keep off'	'expel'	'measure'
breken	*afbreken*	*aanbreken*	*afspreken*	*beklimmen*
'break'	'break off'	'open, begin'	'arrange'	'climb'
brengen	*wegbrengen*	*volbrengen*	*verlengen*	*opdrogen*
'bring'	'deliver'	'accomplish'	'extend'	'dry up'
dekken	*bedekken*	*ontdekken*	*uitlekken*	*uitkiezen*
'cover'	'cover'	'discover'	'leak'	'select'
denken	*nadenken*	*verdenken*	*inschenken*	*verbranden*
'think'	'think'	'suspect'	'pour'	'burn'
dragen	*meedragen*	*opdragen*	*aanklagen*	*verbranden*
'carry'	'carry'	'commission'	'sue'	'burn'
drinken	*opdrinken*	*verdrinken*	*bezinken*	*instoppen*
'drink'	'drink up'	'drown'	'sink'	'put in'
geven	*aangeven*	*begeven*	*inleven*	*opblazen*
'give'	'hand'	'break down'	'empathize'	'blow'
grijpen	*vastgrijpen*	*begrijpen*	*uitknijpen*	*uitlachen*
'grab'	'grasp'	'understand'	'squeeze out'	'ridicule'
halen	*afhalen*	*herhalen*	*afdwalen*	*uitpluizen*
'take, get'	'pick up'	'repeat'	'stray off'	'unravel'
hangen	*ophangen*	*afhangen*	*ontvangen*	*verschuilen*
'hang'	'hang'	'depend on'	'receive'	'hide'
houden	*behouden*	*ophouden*	*aanschouwen*	*vermijden*
'keep'	'retain'	'stop'	'see'	'avoid'
kennen	*herkennen*	*bekennen*	*wegrennen*	*afscheiden*
'know'	'recognize'	'confess'	'run away'	'secrete'
kijken	*bekijken*	*verkijken*	*ontwijken*	*opvragen*
'look'	'see'	'make a mistake'	'avoid'	'request'
kopen	*inkopen*	*bekopen*	*ontknopen*	*opduiken*
'buy'	'buy'	'pay dearly'	'solve'	'surface'
krijgen	*verkrijgen*	*afkrijgen*	*opstijgen*	*ontvoeren*
'get'	'obtain'	'complete'	'ascend'	'kidnap'
lopen	*doorlopen*	*verlopen*	*omdopen*	*bewaken*
'walk'	'walk, hurry'	'expire'	'rename'	'guard'
maken	*aanmaken*	*uitmaken*	*afkraken*	*aanvoelen*
'make'	'prepare'	'extinguish, break up'	'run down'	'sense'
nemen	*aannemen*	*vernemen*	*verlenen*	*opvouwen*
'take'	'take'	'find out'	'give, grant'	'fold up'
rotten	*verrotten*	*oprotten*	*bespotten*	*aanspannen*
'rot'	'decay'	'piss off'	'ridicule'	'rig, yoke'
schieten	*beschieten*	*opschieten*	*begieten*	*bezoeken*
'shoot'	'fire on/at'	'hurry up'	'pour over'	'visit'
schrijven	*opschrijven*	*toeschrijven*	*inwrijven*	*opeten*
'write'	'write up'	'attribute'	'rub in(to)'	'eat'
sluiten	*afsluiten*	*besluiten*	*uitbuiten*	*verschijnen*

(*continued on next page*)

Table 9 (*continued*)

Target	MS prime	M prime	Ph prime	C prime
'close'	'close'	'choose, decide'	'exploit'	'appear'
steken	*neersteken*	*afsteken*	*inweken*	*omfietsen*
'stab'	'stick out'	'let off'	'soak'	'cycle round'
tikken	*aantikken*	*vertikken*	*aandikken*	*vervloeken*
'tap'	'tap'	'refuse'	'embroider'	'curse'
trappen	*vertrappen*	*betrappen*	*aanpappen*	*opwachten*
'kick'	'trample'	'catch s/o'	'chum up'	'wait for s/o'
trekken	*optrekken*	*vertrekken*	*uitstrekken*	*verslapen*
'pull'	'pull up'	'leave'	'stretch (out)'	'oversleep'
vallen	*omvallen*	*bevallen*	*uitstallen*	*bijkomen*
'fall'	'topple'	'give birth, satisfy'	'display'	'recover'
wegen	*afwegen*	*bewegen*	*verplegen*	*opbellen*
'weigh'	'weigh'	'move'	'nurse'	'call up'
wennen	*aanwennen*	*verwennen*	*afremmen*	*bezweren*
'get used to'	'get used to'	'pamper'	'slow down, brake'	'swear'
werpen	*afwerpen*	*ontwerpen*	*aanscherpen*	*uitdraaien*
'throw'	'throw off'	'design'	'sharpen'	'print out'
wijzen	*aanwijzen*	*bewijzen*	*vergrijzen*	*uitgraven*
'point'	'point out'	'prove'	'age, get old'	'excavate'
wonen	*bewonen*	*bijwonen*	*bekronen*	*verslijten*
'live'	'inhabit'	'attend'	'award'	'wear out'
zetten	*neerzetten*	*bezetten*	*invetten*	*besproeien*
'put'	'put down'	'occupy'	'grease'	'sprinkle'

Appendix C

C.1. Stimuli Experiment 2

See Table 10

Table 10
Stimuli in Experiment 2, for the target (i.e., the stem + infinitival morpheme) and the primes in the Morphologically and Semantically related (MS), only Morphologically related (M), Semantically related (S), and Control (C) conditions. Stimuli other than the S primes which were not included in Experiment 1 are indicated with an asterisk.

Target	MS prime	M prime	S prime	C prime
bieden	*aanbieden*	*verbieden*	*verlenen*	*opjagen*
'offer'	'offer'	'forbid'	'give, grant'	'rush'
bijten	*afbijten*	*verbijten*	*toehappen*	*verhuren*
'bite'	'bite off'	'suppress'	'snap, bite'	'lease'
blijven	*verblijven*	*afblijven*	*voortduren*	*opmeten*
'stay'	'stay'	'keep off'	'persist'	'measure'
breken	*afbreken*	*aanbreken*	*vernielen*	*beklimmen*
'break'	'break off'	'open, begin'	'wreck, ruin'	'climb'
brengen	*wegbrengen*	*volbrengen*	*bezorgen*	*opdrogen*
'bring'	'deliver'	'accomplish'	'deliver'	'dry up'
dekken	*bedekken*	*ontdekken*	*afschermen*	*uitkiezen*
'cover'	'cover'	'discover'	'shield, cover'	'select'
denken	*nadenken*	*verdenken*	*beraden*	*verscheuren*
'think'	'think'	'suspect'	'consider'	'tear, rip'
dragen	*meedragen*	*opdragen*	*meetorsen*	*verbranden*
'carry'	'carry'	'commission'	'carry along'	'burn'
drinken	*opdrinken*	*verdrinken*	*opslorpen*	*instoppen*
'drink'	'drink up'	'drown'	'sip, absorb'	'put in'
geven	*aangeven*	*begeven*	*verstrekken*	*opblazen*
'give'	'hand'	'break down'	'supply with'	'blow'
grijpen	*vastgrijpen*	*begrijpen*	*vastpakken*	*uitlachen*
'grab'	'grasp'	'understand'	'grab'	'ridicule'
halen	*afhalen*	*herhalen*	*bereiken*	*uitpluizen*
'take, get'	'pick up'	'repeat'	'reach'	'unravel'
hangen	*ophangen*	*afhangen*	*vastkleven*	*verschuilen*

(*continued on next page*)

Table 10 (*continued*)

Target	MS prime	M prime	S prime	C prime
'hang'	'hang'	'depend on'	'stick'	'hide'
houden	*behouden*	*ophouden*	*bewaren*	*vermijden*
'keep'	'retain'	'stop'	'keep'	'avoid'
kennen	*herkennen*	*bekennen*	*beheersen*	*afscheiden*
'know'	'recognize'	'confess'	'have command of'	'secrete'
*keren**	*omkeren**	*uitkeren**	*omdraaien*	*omlijnen**
'turn'	'turn back'	'pay (out)'	'turn (round)'	'delineate'
kijken	*bekijken*	*verkijken*	*aanschouwen*	*opvragen*
'look'	'see'	'make a mistake'	'see'	'request'
*komen**	*meekomen**	*omkomen**	*verschijnen*	*vergissen**
'come'	'come (along)'	'die'	'appear'	'mistake'
kopen	*inkopen*	*bekopen*	*aanschaffen*	*opduiken*
'buy'	'buy'	'pay dearly'	'procure, purchase'	'pop up'
krijgen	*verkrijgen*	*afkrijgen*	*ontvangen*	*ontvoeren*
'get'	'obtain'	'complete'	'receive'	'kidnap'
lopen	*doorlopen*	*verlopen*	*bewandelen*	*bewaken*
'walk'	'walk, hurry'	'expire'	'walk (on)'	'guard'
maken	*aanmaken*	*uitmaken*	*verstellen*	*aanvoelen*
'make'	'prepare'	'extinguish, break up'	'repair'	'sense'
nemen	*meenemen**	*vernemen*	*gebruiken*	*opvouwen*
'take'	'take with'	'find out'	'take to use'	'fold up'
*roeren**	*omroeren**	*ontroeren**	*vermengen*	*aankleden**
'stir'	'stir'	'touch, move'	'mix'	'get dressed'
rotten	*verrotten*	*oprotten*	*bederven*	*aanspannen*
'rot'	'decay'	'piss off'	'decay, spoil'	'rig, yoke'
schieten	*beschieten*	*opschieten*	*afvuren*	*bezoeken*
'shoot'	'fire on/at'	'hurry up, push on'	'fire'	'visit'
schrijven	*opschrijven*	*toeschrijven*	*berichten*	*opeten*
'write'	'write up'	'attribute'	'send word'	'eat'
sluiten	*afsluiten*	*besluiten*	*opheffen*	*vermalen**
'close'	'close'	'choose, decide'	'discontinue'	'grind'
*spreken**	*toespreken**	*afspreken**	*vertellen*	*aanrijden**
'speak'	'speak to'	'agree (on), arrange'	'tell'	'run down'
steken	*neersteken*	*afsteken*	*inprikken*	*omfietsen*
'stab'	'stick out'	'let off'	'prick'	'cycle round'
tikken	*aantikken*	*vertikken*	*bekloppen*	*vervloeken*
'tap'	'tap'	'refuse'	'tap'	'curse'
trappen	*vertrappen*	*betrappen*	*wegschoppen*	*opwachten*
'kick'	'trample'	'catch s/o'	'kick away'	'wait for s/o'
trekken	*optrekken*	*vertrekken*	*ophijsen*	*verslapen*
'pull'	'pull up'	'leave'	'raise'	'oversleep'
vallen	*omvallen*	*bevallen*	*neerstorten*	*uitdagen**
'fall'	'topple'	'give birth, satisfy'	'crash'	'challenge'
wegen	*afwegen*	*bewegen*	*bepalen*	*opbellen*
'weigh'	'weigh'	'move'	'determine'	'call up'
wennen	*aanwennen*	*verwennen*	*aanpassen*	*bezweren*
'get used to'	'get used to'	'pamper'	'adapt to'	'swear'
werpen	*afwerpen*	*ontwerpen*	*weggooien*	*verbuigen**
'throw'	'throw off'	'design'	'throw away'	'bend'
wijzen	*aanwijzen*	*bewijzen*	*aanduiden*	*uitgraven*
'point'	'point out'	'prove'	'indicate'	'excavate'
wonen	*bewonen*	*bijwonen*	*vertoeven*	*verslijten*
'live'	'inhabit'	'attend'	'stay'	'wear out'
zetten	*neerzetten*	*bezetten*	*verplaatsen*	*besproeien*
'put'	'put down'	'occupy'	'move, relocate'	'sprinkle'

Appendix D

D.1. Additional Linear Mixed Effects Model, Experiment 1

See Table 11

Table 11
LME Model summary for the analysis of RT data in Experiment 1, with the reference level of PRIMECONDITION set to the M condition.[a]

	Log-transformed RT		
Fixed Effects	*Estimate* (β)	*t-value*	*p-value*
(Intercept)	6.71	404.283	**<.001**
Prime Condition (M)			
C	0.10	8.150	**<.001**
MS	−0.02	−1.377	.169
Ph	0.08	6.378	**<.001**
Prime Prefix	0.02	2.634	**.008**
Trial Number	−0.04	−9.543	**<.001**
ISI	0.00	0.159	.874
Target Frequency	−0.02	−2.631	**.009**
Prime Frequency	0.02	3.515	**<.001**
Target Neighborhood Density	−0.01	−1.272	.203
Target Duration	0.07	9.831	**<.001**
Prime RT (log)	0.05	11.041	**<.001**
Random Effects	*N*	*Variance*	*St. dev*
Primes	143	0.0003	0.018
Targets	36	0.0009	0.030
Subjects	32	0.0057	0.076
Residual		0.0157	0.126
N Datapoints	1055		

[a] Significant *p*-values ($p < 0.05$) are shown bold faced.

Appendix E

E.1. Additional Linear Mixed Effects Models, Experiment 2

See Tables 12 and 13

Table 12
Linear Mixed Effects Model for analysis of Experiment 2, with the reference level of PRIMECONDITION set to the MS condition, and the reference level of DISTANCE set to 0-lag.[a]

	Log-transformed RT		
Fixed Effects	*Estimate* (β)	*t-value*	*p-value*
(Intercept)	6.80	320.784	**<.001**
Prime Condition (MS)			
C	0.06	3.848	**<.001**
M	−0.01	−0.375	.708
S	0.04	3.065	**.002**
Distance 5-lag	0.07	5.356	**<.001**
Prime Prefix	0.00	0.199	.842
Trial Number	−0.02	−3.165	**.002**
ISI	0.00	0.560	.576
Target Frequency	−0.01	−1.910	.056
Prime Frequency	0.00	1.111	.267
Target Neighborhood Density	−0.01	−1.948	.051
Target Duration	0.06	9.016	**<.001**
Prime Condition C: Distance 5-lag	−0.06	−3.627	**<.001**
Prime Condition M: Distance 5-lag	−0.01	−0.529	.597
Prime Condition S: Distance 5-lag	−0.04	−2.194	**.028**
Random Effects	*N*	*Variance*	*St. dev*
Prime Intercept	160	0.0000	0.000

(*continued on next page*)

Table 12 (*continued*)

		Log-transformed RT	
Targets	40		
Intercept		0.0016	0.040
MS slope		0.0021	0.046
Subjects	40		
Intercept		0.0095	0.098
MS slope		0.0003	0.016
Residual		0.0137	0.117
N Datapoints	1425		

[a] Significant p-values ($p < 0.05$) are shown bold faced.

Table 13
Linear Mixed Effects Model for analysis of Experiment 2, with the reference level of PRIMECONDITION set to the C condition, and the reference level of DISTANCE set to 5-lag.[a]

		Log-transformed RT	
Fixed Effects	*Estimate* (β)	*t-value*	*p-value*
(Intercept)	6.86	362.828	**<.001**
Prime Condition (C)			
MS	0.01	0.507	.612
M	−0.01	−0.561	.575
S	0.01	1.094	.274
Distance 0-lag	−0.00	−0.188	.851
Prime Prefix	0.00	0.199	.842
Trial Number	−0.02	−3.165	**.002**
ISI	0.00	0.560	.576
Target Frequency	−0.01	−1.910	.056
Prime Frequency	0.00	1.111	.267
Target Neighborhood Density	−0.01	−1.948	.051
Target Duration	0.06	9.016	**<.001**
Prime Condition MS: Distance 0-lag	−0.06	−3.627	**<.001**
Prime Condition M: Distance 0-lag	−0.05	−3.100	**.002**
Prime Condition S: Distance 0-lag	−0.03	−1.419	.156
Random Effects	*N*	*Variance*	*St. dev*
Prime Intercept	160	0.0000	0.000
Targets	40		
Intercept		0.0016	0.040
MS slope		0.0021	0.046
Subjects	40		
Intercept		0.0095	0.098
MS slope		0.0003	0.016
Residual		0.0137	0.117
N Datapoints	1425		

[a] Significant p-values ($p < 0.05$) are shown bold faced.

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