Research Article

Gemination and degemination in English prefixation: Phonetic evidence for morphological organization

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A B S T R A C T

This paper addresses the problem of morpho-phonological variability and the role of phonetic detail in morphologically complex words by investigating the gemination behavior of the English prefixes *un-* and *in-*. Traditionally, it is assumed that *un-* geminates while *in-* degeminates, but empirical studies are rare and not conclusive. This paper presents the first study that uses data from natural speech (Switchboard Corpus, Godfrey and Holliman 1997). It is shown that both prefixes geminate, contra large parts of the literature. Furthermore, there is a difference in nasal duration between *un-*, negative *in-* and locative *in-*. The more segmentable the prefix the longer the nasal duration. The results challenge widely-shared assumptions in morphological theory, lexical phonology and models of speech production, and support models in which the strength of morphological boundaries may impact on the durational properties of complex words.

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1. Introduction

In languages with phonological geminates, a geminate is taken to be a double consonant which is articulated with a particularly long duration (e.g. Catford, 1988; Crystal, 2008; Hartmann and Stork, 1972; Matthews, 1997; Trask, 1996). Hence, in such languages there is a phonemic difference between a geminate and the corresponding single consonant, like, for example, in Italian *fatto* 'done' versus *fato* 'fate'. The longer duration of geminates can manifest itself in absolute duration, or in duration relative to the preceding vowel ('relative duration', e.g. Miller, 1987; Oh and Redford, 2012; Ridouane, 2010).

In English there is no such phonemic difference. However, two adjacent identical consonants may emerge word-internally through affixation (e.g. *unnatural*) or compounding (e.g. *book case*). What is at issue for English morphological geminates is that there are essentially two possibilities, preservation or reduction. If the two consonants are preserved, we

speak of morphological gemination, if the two consonants are reduced we speak of degemination.[1] In case the two underlying consonants are preserved we expect a significant durational difference between such double consonants and a single consonant, with the double consonant being longer (in either absolute or relative duration).

It is widely believed that the English prefix *in-*, as in *innumerous*, is a classical case of degemination, while *un-*, as in *unnamed*, is believed to geminate. However, the actual facts are not quite clear. There are only two phonetic studies available of morphologically-induced gemination with these prefixes, Kaye (2005) and Oh and Redford (2012). In these experimental studies, the authors found that both prefixes can geminate, but that some pertinent words do not appear to geminate. Overall, these empirical results are somewhat inconclusive, due to the small number of different words that were tested and some methodological problems.

The situation is further muddled by the fact that practically all discussions of the degemination of *in-* in the literature ignore

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[1] Hayes (1986, 468f) suggests different terms for those geminates that are phonological in nature ('true geminates'), and those that arise through morphology ('fake geminates'), a terminological distinction picked up, for example, by Oh and Redford (2012). In this paper we prefer to call adjacent identical consonants that arise through morphological processes 'morphological geminates' (or 'geminates' for short).

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that *in-* actually represents two different prefixes, i.e. negative *in-*, as in *incompetent* or *impossible*, and locative *in-*, as in *infuse* 'to pour in', *implant* 'to plant in', *import* 'to bring in' (all paraphrases from *OED*). If degemination is an affix-specific process (i.e. if some affixes geminate, while other affixes degeminate), locative and negative *in-* could differ in their degemination behavior.

The lack of empirical evidence is unfortunate since gemination may have important implications for theory. First, in Lexical Phonology the gemination behavior of *un-* and *in-* is a stock example of the alleged lexical stratification into level 1 and level 2 morphology. If the actual behavior of the two prefixes is different from what seems to be the received wisdom, this challenges widely-held assumptions of Lexical Phonology.

Furthermore, gemination may have implications for theories of lexical processing and the organization of morphological information in the lexicon. Hay (2007) argues that the phonetic properties of the English prefix *un-* are determined by the word-specific morphological segmentability of the prefix. This view is in line with dual route models of morphological processing that allow both whole-word storage and morphological segmentation. Hay (2003) argues that words with a weaker boundary are more likely to be processed as whole words while words with a strong boundary are more likely to be decomposed. In this approach, boundary strength is taken to be gradient and to be influenced by parameters such as semantic transparency, phonological transparency, and relative frequency. Phonetically, words with weaker boundaries are expected to show more phonetic reduction across the morpheme boundary than words that have a strong boundary. Under this view, gemination can be seen as a reduction phenomenon that is predicted to be dependent on the decomposability of the words in question.[2]

The present paper addresses the problem of morpho-phonological variability and the role of phonetic detail in morphologically complex words by studying the gemination behavior of the English prefixes *un-*, negative *in-* and locative *in-*. We investigate whether these prefixes geminate, testing, for the first time, assumptions from the literature with data from natural speech (Switchboard Corpus Godfrey and Holliman, 1997). Furthermore, we will investigate whether segmentability has an influence on the duration of the nasal in the three prefixes. We show that all three prefixes geminate, thus refuting widely-held beliefs about the degemination of *in-*. We also show that the prefixes differ in nasal duration, with *un-* showing the longest duration and locative *in-* the shortest. These results suggest that nasal duration is dependent on the segmentability of the prefix, since *un-* is the most easily segmentable prefix and locative *in-* the least easily segmentable prefix. These findings support models in which the strength of morphological boundaries may impact the durational properties of complex words.

The paper is structured as follows. In the next section we will take a closer look at the three prefixes. Section 3 will present our methodology. In Section 4 we first test assumptions about the segmentability of the three prefixes, and then present regression models that investigate the effects of singleton versus double nasals, and the effect of segmentability, on

nasal duration. Section 5 discusses the results and concludes the paper.

2. The prefixes *un-* and *in-*

2.1. Point of departure

Assumptions about the gemination behavior of *un-* and *in-* can be gleaned from theoretically oriented studies (e.g. Mohanan, 1986) and from secondary sources such as handbooks, textbooks or pronunciation dictionaries.

Looking at pronunciation dictionaries (e.g. Kenyon and Knott, 1953; Roach et al., 2011; Wells, 2008) one finds a systematic difference between the representations of the prefix *in-* and the prefix *un-*. If an *un-*prefixed word is attached to a base starting in /n/, the word is transcribed with a long nasal (i.e. with [nː]). In contrast, if an *in-*prefixed word attaches to a base starting with /n/ the transcription only shows a short /n/ (i.e. [n]). The only exception we were able to find is the word *innavigable* in Roach et al. (2011), where the word is transcribed with two [n]s.

There is the complication that *in-* has three variants that may or may not involve gemination: *im-*, *ir-* and *il-*, as in *immobile*, *irresponsible* and *illegal*, respectively. In the dictionaries we consistently find a short consonant in these cases, too. That is, all allomorphs of *in-* are taken to behave in the same way with regard to degemination.

The pertinent phonological or morphological literature supports the dictionary writers' take on prefixal gemination. Thus, Wijk (1966, 141), O'Connor (1973, 255), Mohanan (1986, 18), Borowsky (1986, 119ff), Catford (1988, 111), Kreidler (1989, 106), Ladefoged (1993, 251), Harris (1994, 18), Spencer (1996, 22), Cohen-Goldberg (2013, 1055f.), and Cruttenden and Gimson (2014) all agree that *un-* geminates. Remarks on *in-* are less frequent, and often only refer to isolated pertinent words, but those authors who mention the issue of double nasals with *in-* all agree that *in-* degeminates (Mohanan, 1986, 18; Ladefoged, 1993, 251; Harris, 1994, 18ff; Cohen-Goldberg, 2013, 1055f; Cruttenden and Gimson, 2014, 248).

The theoretical literature accounts for the alleged difference in gemination behavior between the two prefixes by positing two different kinds of morphological boundary. Mohanan (1986, 18) and Borowsky (1986, 119ff), in the framework of Lexical Phonology (Kiparsky, 1982 et seq.), assign *in-* to level 1 and *un-* to level 2. In this theory, level 1 affixes have weak morphological boundaries which go along with greater phonological integration with their base, including assimilation and degemination, while level 2 affixes form strong boundaries with their base and are phonologically less integrated. Similar in spirit is Harris' (1994) account, in which the author distinguishes between root affixation (for *in-*) and word affixation (for *un-*). In root-affixation, generally one phoneme is deleted when two identical segments immediately follow each other.

Cohen-Goldberg (2013) attributes the alleged difference in gemination between *in-* and *un-* to their difference in productivity: the less productive prefix *in-* degeminates while the more productive *un-* geminates. Since productivity correlates with morphological segmentability (e.g. Hay and Baayen, 2002; Hay and Plag, 2004; Plag and Baayen, 2009), this approach could be extended to make the explicit prediction that duration

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[2] We use the terms 'decomposable' and 'segmentable' more or less synonymously, with 'segmentability' referring to affixes, and 'decomposability' to the words containing affixes.

should vary across words depending on the decomposability of the word in question. For example, Hay (2007) showed for *un-*prefixed words that more decomposable words had a longer prefix duration than less decomposable words. As a measure of segmentability Hay used relative frequency, i.e. the ratio of the frequency of the derived word and the frequency of the base. In the majority of cases, derivatives are less frequent than their bases, but sometimes the opposite is the case. For example, *government* is more frequent than its base *govern*, which not only leads to a whole-word bias in lexical access, but also manifests itself in phonetic reduction in the derivative. Applied to gemination, less decomposable words should display a shorter nasal duration than more decomposable words. Such an approach may also suggest that there is a three-way durational distinction between *un-*, negative *in-* and locative *in-*.

2.2. Previous empirical studies

There are only two studies that have systematically collected empirical data to investigate whether there is gemination with *un-* and *in-*, Kaye (2005) and Oh and Redford (2012). Both studies investigated gemination in *in-*prefixed words by looking at words that featured the allomorph *im-*. The reason for this is that there are very few *in-*prefixed words with a base starting in /n/. The OED (2013) lists only ten such types, of which several share the same morphological family (*innavigable, innervate, innervation, innocuous, innocuously, innocuousness, innominate, innumerable, innumeracy, innumerate*). For reasons of consistency and simplicity in notation, we will continue to use '*in-*' as a representation of the morpheme, and thus as a proxy for any of the allomorphs of this morpheme.

Kaye (2005) investigated only two *un-*prefixed words (*unknown, unnamed*) and one *in-*prefixed word (*immature*). In an elicitation task, ten speakers produced these words, as well as the words' bases in isolation. Kaye then compared the duration of the nasal in the different words. The results indicate that both prefixes geminate. The [n] in *unknown* is longer than the [n] in *known*, the [n] in *unnamed* is longer than the [n] in *named* and the [m] in *immature* is longer than the [m] in *mature*. Kaye notes, however, that whether an *in-*prefixed word geminates or not depends on the individual speaker. Not all speakers produced the prefixed words with a longer nasal than the base. However, since Kaye did not apply any statistical analyses (beyond computing averages) and only investigated a very limited number of types, the results are somewhat inconclusive. What we can see, however, is that Kaye's empirical data go against the claim that *in-* degeminates.

Oh and Redford's (2012) study on the gemination of *in-* and *un-* compared the duration of morphological geminates with the duration of assumed phonological singletons in words starting with similar phonemic strings. The authors investigated 16 different words which contained two consonants in the orthographic representation. The items were categorized by Korean speakers (i.e. speakers of a language that has phonological geminates) who rated the duration of the nasals as either single or double, based on an English native speaker's pronunciation of these words. The words *immovable, immoral, immemorial, immeasured, unnoticed, unnamed, unnerve, unnail* were categorized as containing a double nasal, while

ammonia, immensely, immunity, immigrational, annex, innate, annoyed, innerve were categorized as words containing a single nasal. The items were then put into carrier sentences and read out by eight participants in two different conditions (normal speech vs. careful speech).[3] The analysis of the durations showed that the items rated by Korean speakers as having double nasals were longer in duration than items rated as having single nasals. This indicates that, quite unexpectedly, at least some words with the prefix *in-* show gemination.

However, there is variation in the gemination pattern of *in-* found by Oh and Redford (2012): the set of words with singletons mainly contains words that are morphologically simplex, but some words are not simplex. The word *immigrational*, for example, is prefixed (compare *migration*, *immigration*), which in turn would mean that in this word, *in-* degeminates while in the other prefixed words it geminates. Note also that *immigrational* (like, arguably, *innate* 'existing in a person [...] from birth', *OED*, s.v. 'innate, adj.'), features the locative prefix, not the negative prefix. Incidentally, both words with locative prefixes ended up in the set of words that do not geminate, while the words with negative *in-* showed gemination.

To summarize, previous research on the gemination behavior of *in-* and *un-* leaves us with a number of unsolved problems. First, there is only little empirical evidence available, which means that the facts essentially are unclear. The evidence from the two pertinent empirical studies calls into question the widely-held assumption that *un-* geminates and *in-* degeminates. Second, existing empirical studies are rather limited in their data sets and consider words spoken under experimental conditions, i.e. read out in isolation or in carrier sentences. What is lacking is data from natural speech. Third, existing studies have never considered the different kinds of *in-*prefixes, locative versus negative, and potential differences between them. Fourth, no study has systematically explored how segmentability might influence the gemination behavior of the three prefixes. The existing literature suggests that the differences in boundary strength between the three prefixes might allow us to formulate predictions arising from Hay's (2003) approach to morphological segmentability. In order to understand these predictions, we need to take a closer look at the properties of the three prefixes.

2.3. Some properties of un-, negative in- and locative in-

The properties of *un-* seem to be rather straightforward. It is highly productive, has a strong morphological boundary and highly transparent derivatives (cf., for example, Bauer et al., 2013, chap. 17). For the two *in-* prefixes the situation is different.

While the existence of the negative prefix *in-* is uncontroversial, the idea of a locative prefix *in-* may not be as straightforward. Locative *in-* belongs to a set of Latinate forms in English that are often discussed in the context of morpheme-based approaches to word structure (e.g. Aronoff, 1976, 12; Bauer et al., 2013, 15f; Don, 2014, 15; Lieber, 2010, 41f; Plag, 2003, 24f). In this set we find historically Latin prefixes such as *ad-*, *con-*, *in-*, *re-*, but also bound roots, for example

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[3] In their terminology careful speech style involved the careful reading of an experimental stimulus in a carrier sentence, while the normal speech style involved reading the sentences "in a normal style" (p. 85).

-ceive, -mit or -fuse. These forms may sometimes have a clear meaning, sometimes not. Depending on which type of definition of morpheme one adheres to, such forms are treated as morphemes (if one's theory allows for morphemes without clear semantic content), or as units below the word level that have no clear semantic content. According to the latter position these strings are called 'formatives' and are considered "elements contributing to the construction of words" (Bauer et al., 2013, 16), and thus as some kind of morphologically relevant unit. Stockwell and Minkova (2001, 91f), (see also Marchand, 1969, 115, 163f) include in- in their set of locative prefixes, alongside 29 other ones, e.g. ad-, circum-, dia-, endo-, inter-, retro-. How can such an analysis be justified?

Let us take the standard methodological approach to morphological categories (cf., for example, Plag, 1999, chap. 5.2.2; Schulte, 2015, 375f; Stockwell and Minkova, 2001, 58ff) according to which an affix should have an identifiable, stable meaning across different words. Under this approach we would consider in- a locative prefix in all those words (and only in those) where the word-initial string in- can be assigned some locative meaning and where at the same time the remaining string is also attested outside that word with a stable, identifiable meaning. Implementing this method, we would be able to assign some locative meaning to the string in- in the pertinent words mentioned in Section 1, as shown by the OED paraphrases: infuse 'to pour in', implant 'to plant in', import 'to bring in'. The remaining strings, i.e. the bases, in these words are all attested (either as words or as bound roots) outside these words with sufficiently similar meaning (cf. transfuse, plant, export). This small sample thus shows that, at least in some words, there is a locative prefix in-.

The locative in- prefix differs in interesting respects from negative in-. While negative in- is "robustly productive in contemporary English" (Bauer et al., 2013, 361), locative in- is not productive (which is the reason why it is not treated at all in Bauer et al. (2013) whose authors only discuss productive morphology in their book (p. 4)). Locative in- also occurs more frequently on bound bases than negative in-, and its derivatives seem more prone to semantic opacity, which makes this prefix less easily segmentable (see Section 4.1 for more detailed discussion). In other words, locative in- seems to have a weaker morphological boundary than negative in-. This difference between negative and locative in- allows us to come up with an interesting prediction concerning their phonetic realization based on Hay's (2003) theory of the relation between phonetic form and morphological segmentability. As already mentioned above, according to this theory, words that are less easily decomposable should show more phonetic reduction. We would therefore expect more reduction, i.e. shorter nasal durations, in words with non-productive locative in- than in words with productive negative in-. And we would expect shorter nasal durations in words with negative in- than in words with un- since un- is the most easily segmentable of the three prefixes.

Such a behavior would be in line with the findings of studies that have also looked at the phonetic correlates of morphological boundaries of varying strength. Smith et al. (2012) discover systematic phonetic differences in the realization of the first three segments between prefixed words and what they call 'pseudo-prefixed' words (such as mistime versus mistake, respectively). Similarly, Sugahara and Turk (2004, 2009) find phonetic differences between the final segments of a monomorphemic stem as against the final segments of the same stem if followed by a suffix. Stems followed by certain suffixes had slightly longer rhymes than their monomorphemic counterparts.

There is also articulatory evidence on the variability of intergestural timing in monomorphemic and complex words which points at incongruities in the representations of homophones. In an EPG study, Cho (2001) found that in Korean, timing of the gestures for [ti] and [ni] shows more variation when the sequence is heteromorphemic (i.e. across a morpheme-boundary) than when it is tautomorphemic (i.e. without straddling a boundary). Sproat (1993) and Sproat and Fujimura (1993) demonstrate that the degree of velarization and the duration of English /l/ varies according to the boundary type at which it occurs. The phoneme is shortest and least dark (i.e. with least retracted dorsum) in word-internal position, longer and darker at a suffix boundary, even longer and darker at a compound boundary, and longest and darkest at a word boundary. Sproat (1993) and Sproat and Fujimura (1993) do not distinguish explicitly between the boundaries of productive and unproductive suffixes, but Lee-Kim et al. (2013) re-interpret findings from Sproat (1993) in such a way that the /l/ at a productive boundary (e.g kneeling) is considerably darker than the /l/ at a non-productive boundary (e.g. tel-ic) or within a monomorphemic word. Based on such results one could expect similar phonetic differences between un-, negative in- and locative in-.

2.4. The present study

In sum, there are two main issues with regard to the behavior of un- and in- in English: The degemination facts are unclear, and it is unclear whether segmentability has an influence on the gemination behavior of the three prefixes. This paper will address these issues by empirically testing previous assumptions about gemination and degemination in English prefixed words and by investigating which factors have an influence on the duration of the boundary-adjacent nasal. Our study will focus on two research questions. First, we want to find out whether un- and in- geminate. To that end we will compare the durations of morphological geminates with the duration of singletons in un- and in-prefixed words. If the [n] in un-words with morphological geminates (e.g. unnatural) is longer than the [n] in un-words with a singleton (e.g. uneven), we can say that un- geminates. If the [n] in in-prefixed words with morphological geminates (e.g. innumerous) is longer than in words with a singleton (e.g. inaccurate) we can say that in-geminates. Second, we want to test whether segmentability has an effect on nasal duration, along the lines of Hay (2003). This will tested in two ways, i.e. by comparing the nasal durations of the three prefixes, and by looking at word-specific effects of segmentability.

We present a corpus-based multivariate study of un- and in-prefixed words. In addition to the variables of interest (i.e. the duration of the nasal, the type of prefix, and measures of segmentability) we will include a number of noise variables to control for the potential influence of intervening variables such as speech rate, lexical frequency or phonetic context. Our methodology will be explained in detail in the next section.

Table 1
Distribution of number of types and tokens of *un-* and *in-* prefixed words in the two data sets.

un-

Environment	Example	Types	Tokens
n#nV	*unnecessary*	6	23
n#C	*unfit*	53	68
n#V	*unable*	42	67
Total		101	158

in-

Environment	*negative* in- Example	Types	Tokens	*locative* in- Example	Types	Tokens
m#mV	*immemorial*	11	68	*immigrant*	5	21
m#C	*impossible*	18	18	*implant*	49	49
Total		29	86		54	70

3. Methodology

3.1. Data

We investigate two different data sets. One data set contains *un-*prefixed words, the other *in-*prefixed words. All words in the data sets were taken from the Switchboard Corpus (Godfrey and Holliman, 1997), which consists of about 2400 two-sided phone conversations among North American speakers of English and contains over 3 million word tokens. Both data sets include words with one underlying nasal at the morphological boundary (e.g. *unfit*), as well as words with two underlying nasals at the morphological boundary (e.g. *unnatural*).

The corpus only contained 17 /ɪn/-prefixed tokens with a double nasal. We find only five different types with these tokens (*innocuous, innovated, innovation, innovative, innovativeness*). Furthermore, out of these five types four share the same root. Because of the low frequency of double nasals with the allomorph /ɪn/ we decided to focus on the allomorph /ɪm/.

As mentioned above, the literature very often is not explicit about the degemination behavior of the different allomorphs of *in-*. If something is said, the authors state that all allomorphs behave in the same way, i.e. all allomorphs of *in-* are taken to undergo degemination (e.g. Borowsky, 1986; Cruttenden and Gimson, 2014). There is thus no obvious reason not to investigate the allomorph /ɪm/ as a representative of the morpheme *in-*. Investigating the allomorph /ɪm/ also has the advantage of giving us the possibility to directly link our results to the two previous studies on gemination which also analyzed /ɪm/ instead of /ɪn/.

We included 90 /ɪm/-prefixed tokens with a double nasal. For the prefix *un-*, the corpus only contained 23 prefixed tokens with a double nasal. We included all of them. We included 70 /ɪm/-prefixed tokens with a single nasal (e.g. *impossible*), and 140 /un/-prefixed tokens with a singleton. 70 of the *un-*prefixed words were followed by a vowel (e.g. *unable*) and 70 were followed by a consonant (e.g. *unfit*). The prefix *in-* only takes the form /ɪm/ when it is followed by homorganic consonants, i.e. by the bilabials /m/, /b/ or /p/. Thus, for the *in-*prefixed words all singletons were followed by a consonant. We included as many types as possible and included only one token of a specific type from one given speaker. Different tokens of the same type thus come from different speakers, and all speakers but two provided only one token per type.[4]

Some of the tokens sampled had to be removed after closer inspection of the sound files, for example because the quality of the recording was insufficient to provide valid segmentation. The final data sets were of comparable size and contained 158 complex words with the affix *un-* and 156 *in-*prefixed words (with the allomorph /ɪm/). Table 1 summarizes the distribution of the prefixes in the final data sets by showing the type and token numbers for each environment described above.

3.2. Acoustic measurements

After extracting the sound files from the Switchboard Corpus, four annotators manually segmented the data and transcribed them phonetically using the software Praat (Boersma and Weenink, 2014).

As one can see in Fig. 1, we annotated the segments of the prefix in question, as well as the segments of the syllable immediately following the prefix under investigation. Double nasals were treated as one segment in the annotation since no boundaries between two identical nasals were discernible. The segmentation criteria layed out in the following were based on the features of specific sounds as described in the phonetic literature (e.g. Ladefoged, 2003).

Nasals have a regular waveform which has a lower amplitude than the waveform of vowels. Formants of nasals are quite low and faint in comparison to those of vowels. Boundaries between the preceding vowel and the nasal were thus set where the acoustic energy drops in the waveform, the spectrogram becomes visibly fainter and the higher formants visibly decrease (see Fig. 1). In case of a following vowel, the boundary was marked at the point where the amplitude increases in the waveform and the formants become clearly visible (see Fig. 1). Approximants following the nasal were identified similarly to a following vowel, since they have, similar to vowels, a higher amplitude than nasals, as well as more acoustic energy. If a stop followed the nasal, the boundary was marked at the beginning of the occlusion, which was identified by the abrupt decrease of the waveform and the sudden diminishment of the formants. In case of a following fricative,

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[4] This exception was made because of the small number of items with double nasals in the *un-*data set.
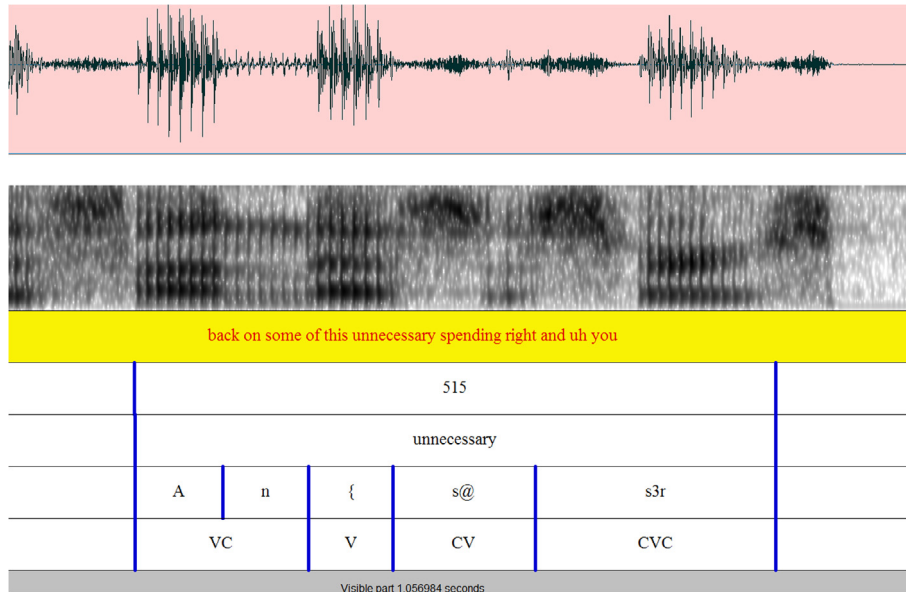
Fig. 1. Acoustic analysis of the item unnecessary.

the boundary was set where the waveform became visibly irregular and the energy was concentrated in the upper part of the spectrogram with no distinct formants visible. All boundaries were set at the nearest zero crossing of the waveform.

The reliability of the segmentation criteria was verified by trial segmentations, in which it was ensured that all annotators placed all boundaries with only small variations. For the final measurement, each annotator worked on a disjunct set of items. After the segmentation process was completed, a script was used to measure and extract word duration, the number of segments in the word, the duration of the nasal in question, as well as the duration of its preceding and following segments in milliseconds.

3.3. Predictor variables

The duration of segments in natural speech is subject to a variety of different influences, and in order to address our research questions these influences need to be controlled for. This can be done by coding the pertinent variables and using them as independent variables in a multiple regression model. We can distinguish variables of interest and noise variables. In our case, the variables of interest are the number of nasals, the affix and morphological segmentability measures. In addition to the variables of interest there are of course many other factors that might influence the duration of segments in speech production, such as speech rate or the following segment.

In what follows we describe the variables that turned out to have a significant effect on nasal duration in our data set. In addition to these variables we also coded a number of other variables, such as the duration of the preceding vowel and of the following vowel, word duration, the presence of a phrasal accent, the number of syllables and segments in the word, position in utterance, and word frequency. None of these variables had a significant effect on the duration of the nasal, neither as a main effect nor in interaction with others.

Number of Nasals and Following Segment. Phonetic studies have shown that the duration of a nasal consonant heavily depends on the neighboring segment. Whereas following vowels lead to shorter nasal durations, following (nonnasal) consonants increase it (Umeda, 1977, 854). We coded the phonological environment in the variable ENVIRONMENT. For the prefix *un-*, three levels reflect three environments: n#nV, i.e. a double /n/ followed by vowel (as in *unnatural*), n#C, i.e. a single /n/ followed by a non-nasal consonant (as in *unfit*),[5] and n#V, i.e. a single /n/ followed by a vowel (as in *uneasy*). For the words prefixed with *in-* we only obtain two levels. The two levels are m#mV (as in *immemorial)* and m#C (as in *impossible*).

Affix. To test whether there is a difference in the duration of the nasal(s) between the prefixes we coded the factor AFFIX, using the three levels un, inNeg and inLoc.

Segmentability. We used four different measures of segmentability: two measures of semantic transparency, relative frequency and type of base. We will discuss each in turn.

Semantic transparency has been used extensively in psycholinguistic research to investigate the question of whether words are processed as wholes or whether they are decomposed into their constituent morphemes (see, for example, Marslen-Wilson, 2009 for an overview). These studies have shown that transparent words are more easily decomposed than non-transparent words. We created two variables to test semantic transparency.

The first one is SEMANTICTRANSPARENCYBINARY, in which we coded for each word whether its meaning was transparent or opaque. If the meaning of the derivative was fully compositional, it was categorized as transparent. We coded as fully compositional those words in which the meaning of the derived word is straighforwardly computed by combining the meaning of the affix with the meaning of the base. Examples of transparent words are *unnatural* and *impossible*, whose meaning can

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[5] There were no words in which /n/ was followed by /m/ or /ŋ/.

be paraphrased as combining the prefixal meaning 'not' with the meaning of the base. Words that did not meet this strict criterion were categorized as `opaque`, as, for example, *impression* or *imposed*.

The second variable we used to measure semantic transparency is SEMANTICTRANSPARENCYRATING. We conducted a survey in which all the complex words included in this study were rated for their decomposability. In an online experiment using LimeSurvey (https://www.limesurvey.org/) native speakers of American English were asked how easy it is to decompose a given word into two meaningful parts on a scale from 1 ("very easy to decompose") to 4 ("very difficult to decompose"). The 58 participants gave reliable judgements, as evidenced by a very high Cronbach's α (α = 0.99, Cronbach, 1951). We coded the median of the ratings for each word (i.e. type) in the variable SEMANTICTRANSPARENCYRATING.

Another measure of decomposability is probabilistic in nature, relative frequency (Hay, 2001, 2003). Relative frequency is defined as the ratio of the frequency of a derived word to the frequency of its base. The more frequent a derivative is in comparison to its base, the higher its relative frequency and the less decomposable it is. We computed the variable RELATIVEFREQUENCY by dividing a word's lemma frequency by its base lemma frequency. Frequencies were extracted from the DVD version of the Corpus of Contemporary American English (COCA) (Davies, 2008), using the query tool *Coquery* (Kunter, 2016). We consider COCA an adequate source for the frequency counts because the data in this corpus come from the same variety of English as the speech data in the Switchboard Corpus, i.e. North American English. Following standard procedures relative frequency was log-transformed to reduce the potentially harmful effect of skewed distributions in linear regression models.

The fourth measure of segmentability is structural in nature and concerns the distinction between bound roots and words as bases. Derivatives with words as bases can be assumed to be more easily decomposed than words that have a bound root as their base. This distinction was coded for each derivative in the variable TYPEOFBASE.

Stress. Stressed syllables tend to have a longer duration than unstressed syllables (e.g. Fry, 1955, 1958; Beckman, 1986; Harrington et al., 1998; Lieberman, 1960, see also Laver, 1994 for an overview). Thus, if /ʌn/ or /ɪm/ bear stress, the nasal in the prefix might be longer. It is uncontroversial that *in-* is normally unstressed, but that there are also some derivatives in which the prefixes carry main stress (e.g ínfinite, ímpotent).

The prefix *un-* is taken to be unstressed, but pronunciation dictionaries such as Wells (2008) note not only unstressed *un-* (as in *unfathomable*), but also secondarily stressed *un-* (e.g. in *undefined*), and optionally stressed *un-* (e.g. in *unleash*). It is unclear on which basis Wells assigns the stress marks. A closer look reveals, however, that a secondary stress mark (or an optional stress mark) is assigned to *un-* when the prefix is followed by an unstressed syllable, and no stress mark is assigned when the prefix is followed by a main-stressed syllable (unless the base is monosyllabic). Irrespective of whether there is any reality to the distinction between secondarily and unstressed *un-* as given in Wells (2008), we coded whether the prefix was followed by a stressed syllable or by an unstressed syllable. This seemed to be potentially relevant as Umeda (1977) found that nasals before unstressed vowels are shorter. A possible explanation for this effect is that the lenghtening of the adjacent stressed syllable spills over to the prefix. The variable STRESSPATTERN was coded with two levels: `beforeStressed` and `beforeUnstressed`.

Speech Rate. We computed the values for the variable SPEECHRATE for each item by dividing the number of segments included in the word by the total word duration in seconds. It is expected that the more segments are produced per second, i.e. the higher the speech rate, and the shorter the duration of the nasal(s) in question will be.

Appendix A gives the distribution of the variables for the two data sets.

3.4. Statistical analysis

To see whether the alleged differences in segmentability between the three prefixes are borne out in our data set, we compared the segmentability measurements across prefixes by using standard statistical tests (i.e. Chi-Square, Kruskal–Wallis).

We then fitted one linear regression model to the *un*-data set and one linear regression model to the *in*-data set. We also lumped the two data sets and fitted a model to this overall data set. In all models the (transformed) absolute duration of the nasal in milliseconds (ABSOLUTENASALDURATION) was used as the dependent variable. We also fitted models with relative duration as the dependent variable, but, similar to the findings in Oh and Redford (2012), these models proved to be much less powerful, and had fewer significant predictors than models that had absolute duration as the dependent variable.[6] We therefore focus on absolute duration in this paper.

The use of mixed effects models was precluded by the data's unnestedness. Almost every item is produced by a different speaker and many items occur only once in the corpus, so that it did not make sense to use these variables as random effects.

Multiple regression is an established and highly successful way to deal with the multitude of factors involved in predicting durational properties of morphemes. While regression models have the advantage of letting us look at the effect of one predictor in the presence of other, potentially intervening, predictors there are also some caveats. Two of them are especially pertinent for our analysis, collinearity and overfitting. Let us first discuss collinearity.

There are a number of measurements that we would want to use in our analysis that are correlated with each other, which can lead to serious problems in regression models ('multicollinearity', e.g. Baayen, 2008, chap. 6). One strategy to deal with collinearity is to include only one of the correlating variables. This is a conservative and safe strategy, which may, however, decrease the power of the model. If collinearity only affects noise variables, another option is to keep the correlating variables in the model but not interpret their individual contribution to the model (cf. Wurm and Fisicaro, 2014). To address potential collinearity problems in this paper we applied both strategies.

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[6] Relative duration was computed as the ratio of the duration of the preceding vowel and the duration of the nasal. The statistical models for relative duration are documented in Tables 13 and 14 in Appendix B.

The other major problem is overfitting. In general, comparatively small data sets like the present ones require the number of parameters in the model to be severely restricted. We therefore tried to include only those noise variables (in addition to the variables of interest) that are well-known to have an influence on nasal duration. To reduce the number of parameters, we also tried to conflate two or more predictors into a single new one, if possible.

We adopted the following modeling strategy, in accordance with established practices in the field (e.g. Baayen, 2008). First, we conducted an initial model incorporating all possible variables. We then looked at the residuals of the model, which need to be normally distributed. If visual inspection revealed that the residuals had a non-normal distribution, we used transformations and the exclusion of outliers to obtain the desired pattern. In the models fitted to the *un-* data set and to the *in-* data set transformation of the dependent variable ABSOLUTENASALDURATION was necessary to alleviate problems of non-linearity (see, for example, Baayen and Milin, 2010 for discussion). Following Plag et al. (2015), we used Box–Cox transformation to identify a suitable transformation parameter λ for a power transformation (Box and Cox, 1964; Venables and Ripley, 2002). The Lambda value indicates the power to which all duration measures are raised to reach best results for normality, given a particular regression model.

We then checked for collinearity in our models by looking at the correlations between potentially correlated variables, and followed the strategies described above. We also tested for interactions.

The regression models were simplified by stepwise excluding insignificant predictors. A predictor was considered significant if its p-value was lower than 0.05, and if the Akaike Information Criterion (AIC) of the model including the predictor was lower than when the predictor was not included.[7]

For the statistical analyses presented in this paper, we used R (R Development Core Team, 2014). The regression analyses were done with the MASS package (Venables and Ripley, 2002). The plots of the models were generated with the visreg package (Breheny and Burchett, 2015). For a plot showing the effect of a variable, all other variables are held constant at the median (for numeric variables) or at the most common category (for factors). For better interpretability of the plots the response variable ABSOLUTENASALDURATION is back-transformed to milliseconds.

4. Results

We will first present the results of the analysis of the segmentability measurements in order to make sure that our assumptions about the three prefixes, as laid out in Section 2, are borne out by our data. Having established that this is the case, we move on to the analyses of the nasal durations.

4.1. Segmentability: the three prefixes

We assume that words in *un-* are the most easily decomposable out of the three morphological categories at issue. Furthermore we assume that words with negative *in-* are gen-

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[7] A lower AIC indicates that a model including the factor has a greater explanatory power than a model without the predictor variable.

Table 2
Transparency by prefix (types), SEMANTICTRANSPARENCYBINARY.

Transparency (binary)	*un-*	Negative *in-*	Locative *in-*
Opaque	0	7	42
Transparent	101	21	13

Table 3
Transparency by prefix (types), SEMANTICTRANSPARENCYRATING.

Transparency rating	*un-*	Negative *in-*	Locative *in-*
1 (most transparent)	101	20	2
2	0	1	13
3	0	4	25
4 (least transparent)	0	4	14

Table 4
Type of base by prefix (types).

Type of base	*un-*	Negative *in-*	Locative *in-*
Bound root	2	7	44
Word	99	22	10

erally more easily decomposable than words with locative *in-*. In this subsection we will take a look at the actual segmentability measures and their distributions across the three prefixes, to see whether our assumptions are borne out by the data.

With regard to semantic transparency, we find the distribution of word types shown in Table 2 (SEMANTICTRANSPARENCYBINARY) and Table 3 (SEMANTICTRANSPARENCYRATING). We can easily see that, according to both measures, types with locative *in-* are generally less transparent than types with negative *in-*. Types in *un-* are most transparent. With regard to the question of bound roots versus words as bases, a similar picture emerges. Table 4 gives the pertinent distribution, which shows that locative *in-*, unlike negative *in-*, has indeed a strong preference for bound roots. The prefix *un-* has hardly any bound roots as bases. The differences between the three prefixes are highly significant (the pertinent test statistics are documented in Table 12 in Appendix 2).

The relative frequencies are also distributed as expected. Words with locative *in-* have a mean log relative frequency of 1.56 (sd = 3.64) while words with negative *in-* have a mean of −0.21 (sd = 4.28, all figures are rounded). Words with *un-* have a mean relative frequency of −0.97 (sd = 2.76). Again the difference is highly significant.

To summarize, our assumptions about the three prefixes are correct. Derivatives with locative *in-* are less semantically transparent, have a stronger tendency to be based on bound roots and have a higher relative frequency than derivatives with negative *in-*. Derivatives in *un-* are the most easily decomposable, as evidenced by all measures. In short, we have a cline of segmentability from locative *in-* to negative *in-* to *un-*.

4.2. Duration: overview

Table 5 gives a summary of the durations of the nasals in the two data sets for each environment. In both data sets one can see that the mean and the median for the double nasal (n#nV and m#mV) is higher than the one of the single nasals (n#C, n#V and m#C, respectively). Generally, nasal durations

Table 5
Duration of nasal(s) in milliseconds for *un-* and *in-*

un-

Environment	Example	Mean	Median	Standard deviation
n#nV	*unnecessary*	100	102	21
n#C	*unfit*	64	60	24
n#V	*unable*	45	40	18
Overall		60	54	28

in-

Environment	Example	Mean	Median	Standard deviation
m#mV	*immemorial*	87	81	27
m#C	*impossible*	61	61	19
Overall		76	74	27

vary a great deal by phonological environment. Overall, however, the durations of the nasals in our data set are in the same range as those found in other studies. For example, Umeda (1977, Tables II and X) finds in her North American English data that word-internal singleton /n/ in monomorphemes is 38 ms long on average if followed by a vowel in stressed position, and 34 ms if followed by a vowel in unstressed position.[8] Word-initial singleton /n/ is 71 ms long on average in that study, while double /n/s across a word boundary have a duration of 100 ms.

In the following three subsections we first present separate models for *un-* and *in-*. We then present a model in which *un-*, negative *in-* and locative *in-* are compared.

4.3. Duration: the prefix un-

A model was fitted according to the procedure described above. The Box-Cox transformation parameter for the dependent variable (absolute duration of nasal for *un-*-prefixed words) was 0.3030303. Of the four segmentability measurements only relative frequency was used as a predictor because the other segmentability measures showed distributions that precluded their inclusion into the model due to lack of sufficient variation (see again Tables 2–4). We tested two-way interactions of all variables of interest with all other predictors.

The residuals showed a non-normal distribution. Following standard procedures (e.g. Baayen and Milin, 2010; Crawley, 2002), we removed outliers (defined as items with standardized residuals exceeding −2.5 or +2.5) and refitted the model (thus two observations, i.e. 1.3%, were excluded). This resulted in a satisfactory distribution of residuals. After model simplification only two significant predictors remained, ENVIRONMENT and SPEECHRATE. The model explains 56% of the variation found in the data (Adjusted R-squared: 0.562). The adjusted R-squared for a model with only SPEECHRATE is 0.254, a model with only ENVIRONMENT has an R-squared value of 0.444. This shows that ENVIRONMENT is the much stronger predictor.

Table 6 documents the estimates for each predictor and their *p*-values as found in the final model.

Table 6 shows that with increasing speech rate, the duration of the nasal in *un-*prefixed words decreases (Estimate = −0.008). The higher the speech rate, i.e. the more seg-

ments are pronounced in a shorter amount of time, the shorter becomes the nasal. This is an expected effect. Relative frequency did not turn out to be a significant predictor.

Let us now turn to our variable of interest, ENVIRONMENT. The coefficients for n#C and n#V both go in the same direction and are highly significant. Words containing a double nasal have a significantly longer duration than words with one nasal, no matter whether the single nasal is followed by a non-nasal consonant or by a vowel. In the case of a following vowel, the single /n/ is shortest. Fig. 2 illustrates this effect.

The predicted mean duration for double nasals is 90 ms. For words with the n#C environment the nasal is predicted to be 63 ms long, and for words having the n#V environment it is predicted to be 43 ms long. If we compare the two environments with a following vowel (and thus hold the type of following segment constant), the model predicts double nasals to be even a bit longer than twice the duration of the average single nasal in this environment (90 ms as against 43 ms). This result clearly speaks in favor of gemination with *un-*.

When a consonant follows the single nasal at the morpheme boundary, we also find a highly significant contrast between the two environments, but the difference is smaller. We do not find twice the duration for the double nasal, but only a difference of 27 ms, i.e. an increase in duration of 43% from single to double nasal.

The question may be raised whether this increase in phonetic duration can be interpreted as gemination in spite of the fact that the duration is not doubled. The literature on phonological gemination has shown, however, that the durational differences between geminates and their corresponding singletons may vary substantially (see, for example Aoyama, 2001; Aoyama and Reid, 2006; Cohn et al., 1999; Galea et al., 2014; Ham, 2001; Ladefoged and Maddieson, 1996; Mattei and Di Benedetto, 2000). For morphological geminates across word boundaries, Delattre (1968) has demonstrated that different languages show different singleton-to-geminate duration ratios. For English, he finds an increase from singleton to geminate /n/ of 50%. The geminates in that study straddled a word boundary and were surrounded by vowels (as in *I've seen Nelly*). Umeda (1977) finds in her data that a word-initial nasal is 71 ms long, and that a geminate straddling a word-boundary is 100 ms long (again, in exclusively vocalic environments). Oh and Redford (2012, 86, Fig. 2) arrive at an estimated 82 ms for word-internal singletons, 110 ms for *un*-geminates, and 131 for geminates across word boundaries (again, only vocalic environments were tested).[9]

It thus seems that neither phonological gemination nor morphological gemination necessarily go together with a doubling of phonetic duration, but both types of gemination can result in much smaller durational increases. There is thus good reason to believe that even the smaller of the two contrasts in our data (i.e. the one between n#C vs. n#nV) can be interpreted as good evidence for gemination. The longer duration of the pre-consonantal (as against the pre-vocalic) singleton /n/, which results in a smaller durational difference to the geminate, can be attributed to the type of following segment (C vs. V).

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[8] Throughout this article, measurements reported in milliseconds are rounded.

[9] Oh and Redford (2012) do not give the estimated means in their article. The figures given here are read off from the partial effects plot given in Fig. 2 of their article.

Table 6
Summary of linear model predicting the Box-Cox transformed duration of [n] in *un*-prefixed words. The reference level of ENVIRONMENT is n#nV.

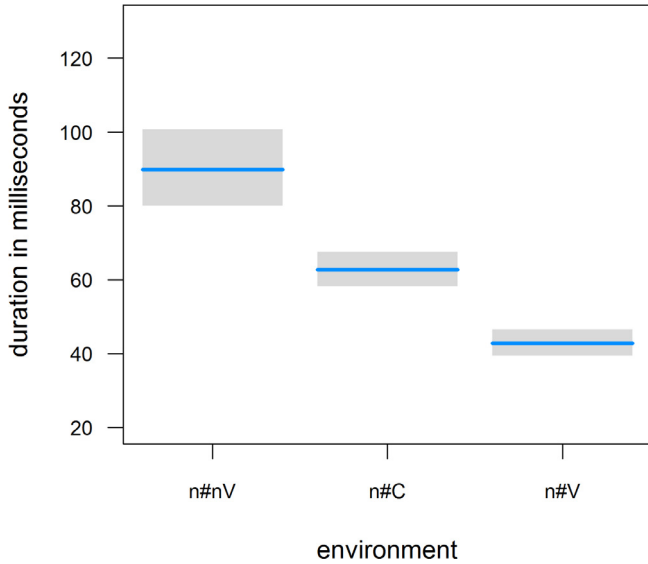|	Estimate	Std. Error	*t*-value	*p*-value
Intercept	0.580	0.015	38.502	<2e−16
ENVIRONMENT − n#C	−0.050	0.010	−5.072	1.13e−06
ENVIRONMENT − n#V	−0.097	0.010	−9.770	<2e−16
SPEECHRATE	−0.008	0.001	−6.814	2.08e−10

Fig. 2. Effect of environment on nasal duration in *un*-data set.

4.4. Duration: the prefix in-

The model for the *in*- data set was fitted according to the same procedure as the previous model, including all seg-

mentability measures. The four measures are, however, highly correlated with each other, with the positive correlation coefficients ranging between 0.42 and 0.63, and the negative ones between −0.46 and −0.79 (Spearman, *p* = 0 for all six correlations). We therefore devised different models, each of which included only one of the segmentability measurements. We also tested two-way interactions of all variables of interest with all other predictors.

The Box–Cox transformation of the dependent variable ABSOLUTENASALDURATION resulted in a transformation parameter of 0.4646465. The final model showed a satisfactory distribution of residuals and explains about 51% of the variation (Adjusted R-squared = 0.514). An overview of the model coefficients is given in Table 7.

The final model includes four variables with a significant effect on nasal duration: ENVIRONMENT, SPEECHRATE, STRESSPATTERN and AFFIX. The higher the speech rate, the shorter the nasal. With an estimated mean duration of 75 ms, the nasal is 21 ms shorter before an unstressed syllable than before a stressed syllable (96 ms). This result is expected, too. As mentioned in Section 3.4, Umeda (1977) also found that nasals before unstressed vowels are shorter than before stressed vowels.

Let us turn to the variables of interest. The left panel of Fig. 3 displays the effect of ENVIRONMENT. Double nasals are significantly longer than singletons. The estimated mean duration for double nasals is 96 ms, while it is 69 ms for single nasals, a difference of 27 ms. This difference is significant, and shows that *in*- geminates.

However, one could venture the idea that the difference is not due to a difference between one nasal and two, but due to a difference in the following segment, i.e. consonant versus

Table 7
Summary of linear model for variables predicting the Box-Cox-transformed duration of [m]. Reference levels are m#mV for ENVIRONMENT, beforeStressed for STRESSPATTERN, and inLoc for AFFIX.

	Estimate	Std. Error	*t* value	*p*-Value
Intercept	0.364	0.014	25.199	<2e−16
ENVIRONMENT-m#C	−0.046	0.007	−6.661	4.75e−10
SPEECHRATE	−0.003	0.001	−4.324	2.77e−05
STRESSPATTERN-beforeUnstressed	−0.036	0.008	−4.647	7.29e−06
AFFIX-inNeg	0.020	0.007	2.742	0.007

Fig. 3. Effects of environment and affix on nasal duration for words prefixed with *in*-.

vowel. This idea is, however, unsupported, since following vowels lead to shorter durations of the nasal, as can also be seen in the *un*-data set, in which a single nasal preceding a consonant (63 ms) is longer than a single nasal preceding a vowel (43 ms). In other words, the double nasals (which are by their very nature followed by a vowel) are likely to be shortened, not lengthened due to their environment. In other words, the double nasals show longer duration in spite of being in an environment that would trigger shorter duration. The significant difference between `m#mV` and `m#C` is thus a sure sign of gemination.

The effect of Affix is displayed in the right panel of Fig. 3. The nasal in negative *in-* is significantly longer (by 12 ms) than the one in locative *in-*. Hence, there is a difference in the duration of the nasal depending on which of the two affixes is used. There was no interaction of Environment and Affix, which means that the two prefixes do not differ significantly in their gemination behavior.

None of the segmentability measures reached significance when entered individually into the models. We return to this point in our discussion.

4.5. Duration: comparing the three prefixes

Let us now turn to the question of whether the segmentability differences between the three prefixes go together with duration differences along the lines of Hay's (2003) theory. Unfortunately, it is not possible to directly compare the durations of the three prefixes as estimated by the regression models presented in the previous sections since the two models have different predictors and different reference levels for these predictors. To meaningfully compare all three prefixes it is therefore necessary to fit a model with the two data sets combined. A model with all three prefixes has the disadvantage, however, that for some variables, we cannot measure their influence across *un-* and *in-* since the *un-* data set and the *in-* data set differ in important respects. Let us look at those differences and what the implications of these differences are for our analysis.

First, the prefix *un-* and the allomorph of *in-* that is being invested here end in two different consonants, i.e. /n/ vs. /m/, so that durational differences between *un-* and *im-* are not straightforward in their interpretation. We used scaling of the durational variables to address this problem.

Second, the phonological environments of singleton *un-* and singleton *im-* are not the same, since *im-* is necessarily always followed by a base-initial consonant, while *un-* is followed by both consonants and vowels. Only the double nasal

in both prefixes is always followed by a vowel. With regard to a comparison of the three prefixes, the model can therefore only tell us something about the following two environments: double nasals followed by a vowel, and single nasals followed by a consonant.

Third, the direct influence of segmentability measures cannot be tested in an interesting way. This is because *un-* does not vary in semantic transparency (all *un-* words are transparent, only *in-* varies), and because relative frequency measures are not well comparable across *un-* and *in-*. The latter problem arises because *in-* has very many bound roots, which is problematic with regard to computing relative frequency measures that are comparable with those of affixes with hardly any or no bound roots. The fact that *un-* has hardly any bound roots as bases is also a problem for the structure-based measure of segmentability, i.e. bound root vs. word as base.

Although not all variables can be used, a regression model can still meaningfully test duration differences between the three prefixes across two crucial environments: double nasals followed by a vowel, and single nasals followed by a consonant. According to the segmentability hypothesis we should expect differences in duration that correlate with the overall segmentability of the three prefixes as found in Section 4.1.

We fitted a regression model to the lumped data sets. To tease the effects of environment apart and to be able to make the crucial comparison for the two pertinent environments (i.e. double nasals followed by a vowel, and single nasals followed by a consonant), we created a new variable in which we coded whether the word has one or two underlying nasals (NumberOfNasals), and an additional variable encoding whether a vowel or a consonant followed the nasal (FollowingSegment). We included the following predictors: NumberOfNasals, FollowingSegment, SpeechRate, StressPattern, Affix, the duration of the preceding vowel, the presence of a phrasal accent and word form frequency. We also tested all two-way interactions of Affix and all other predictors. The final model is documented in Table 8. Negative coefficients indicate shorter durations, positive coefficients longer durations.

We find a main effect of Affix. The coefficients show that negative *in-* is significantly longer than locative *in-* and that *un-* is significantly longer than negative *in-*. These differences are fully in line with the cline of segmentability found in Section 4.1, with the most easily segmentable prefix (i.e. *un-*) being longest, and the least easily segmentable (i.e. locative *in-*) being shortest.

We also find an effect of the number of nasals: Double nasals are significantly longer than singletons. Crucially, there

Table 8
Summary of linear model for variables predicting the normalized duration of the nasal in *un-* and *in-*-prefixed words. Reference levels are `single` for NumberOfNasals, `consonant` for FollowingSegment, `beforeStressed` for StressPattern, and `inNeg` for Affix.

	Estimate	Std. Error	*t* value	*p*-Value
Intercept	2.484	0.223	11.127	<2e−16
NumberOfNasals-`double`	1.454	0.144	−10.065	<2e−16
FollowingSegment-`vowel`	−0.537	0.130	−4.136	4.57e−05
SpeechRate	−0.088	0.012	−7.016	1.46e−11
StressPattern-`beforeUnstressed`	−0.347	0.103	−3.365	0.001
Affix-`inLoc`	−0.469	0.133	−3.521	0.001
Affix-`un`	0.343	0.123	2.794	0.006

Adjusted R-squared: 0.49.

is no significant interaction between AFFIX and NUMBEROFNASALS, which means that all three prefixes geminate.

In addition to these effects of the variables of interest, we find the expected effect of speech rate (nasals become shorter with increasing speech rate) and the expected effect of the following segment (nasals are shorter before vowels). We also find an effect of STRESSPATTERN such that the nasal is shorter before unstressed syllables. None of the interactions was significant.

4.6. Summary

Regarding our variables of interest, all models revealed that items containing a double consonant, i.e. a n#nV or a m#mV structure, showed significantly longer nasal durations than words with only a single underlying nasal, i.e. a n#C, n#V or a m#C structure, respectively. For those data for which the type of following segment was the same (i.e. a vowel), nasal duration more than doubled, which is a clear indication of gemination.

Keeping the environment constant across *un-* and *in-*, i.e. if we compare the double nasal duration with the duration of the nasal before consonant, the two prefixes display very similar duration differences. The model for *un-* predicts 27 ms difference, and the model for *in-* 27 ms difference, too.[10]

Furthermore, with regard to *in-* the duration of the nasal depends on which prefix it represents. The nasal duration in items in which *in-* has a negative meaning is longer than in items where *in-* has a locative meaning. The model that included all three prefixes showed also a difference in the same direction between negative and locative *in-*. Words with the prefix *un-* have the longest nasal durations.

In all models the phonetic variable SPEECHRATE had the expected effect on nasal duration. The higher the speech rate, the shorter the duration of the nasal. In the lumped data set we also observed an influence of STRESSPATTERN on nasal duration, in the expected direction. In the separate models for *un-* and *in-* STRESSPATTERN only had an effect for *in-*. The reason for a lack of the effect in the *un-* data set might be the uneven distribution of the different stress patterns in this data set. Furthermore, the absence of an interaction of STRESSPATTERN and prefix in the lumped data set, and the simultaneous absence of the effect in the *un-* data set may also hint at the lack of statistical power in this rather small data set.

5. Discussion and conclusion

While the majority of the literature agrees on the assumption that *un-* geminates and *in-* degeminates, the empirical data investigated in this study show that *un-* and both *in-* prefixes geminate. For *un-*prefixed words and for *in-*prefixed words the morphological geminates displayed a significantly longer duration than their singleton counterparts. The present study thus replicates earlier experimental findings by Kaye (2005) and Oh and Redford (2012) with natural conversation data

and does so for a larger set of pertinent words.

There are also some interesting smaller differences between this study and Oh and Redford's. Oh and Redford find that the durational difference between geminated and ungeminated nasals depends on the prefix (or the type of nasals, i.e. /n/ or /m/). In the careful speech elicited in their experiment the durational difference between singletons and doubles is larger for *un-* than for *in-*. In the normal speech style elicited in their experiment the difference between *un-* and *in-* is significantly smaller. It can therefore be expected that in natural conversational speech the difference will become even smaller, so that it is not surprising that we do not find a difference between *un-* and *in-* concerning the durational difference between singletons and double nasals.

The fact that the prefix *in-* clearly geminates refutes widely-held assumptions about the gemination pattern of this prefix and challenges the alleged systematic difference between *un-* and *in-*. One reason for the discrepancies between, for example, the dictionaries and the theoretical literature on the one hand, and the results of the present and the other two empirical studies on the other hand, might be that careful reading out of isolated written words may result in pronunciations that significantly deviate from those in casual speech. The results from experimental data such as those of Oh and Redford (2012) combined with the present results from natural conversational speech strongly suggest an influence of speech style, and perhaps even spelling, on gemination in the expected direction.

In a recent article, Tucker and Ernestus (2016) demonstrate that there are indeed many differences between careful and casual speech, some of them expected, some of them less expected. The authors argue that research on casual speech is "necessary to show the validity of conclusions based on careful speech" (p. 300) and claim that studies of casual conversations "will provide information that cannot be revealed by studies on careful speech and will raise new and important questions" (p. 393). The present study is a case in point.

The empirical facts also invalidate the idea put forward by proponents of Lexical Phonology that *in-* as a level 1 prefix should degeminate. Our results tie in with other research that has found variable behavior of affixes with regard to the alleged level a given suffix should belong to. For example, Giegerich (1999, chap. 2) discusses a long list of affixes that show a morpho-phonological behavior that suggests double membership for these affixes. The prefix *in-* is somewhat similar, in that it geminates, i.e. shows a level 2 behavior, but nevertheless shows assimilation, which is taken to be a level 1 characteristic (e.g. Borowsky, 1986). This is further evidence that each affix comes with its own morpho-phonological restrictions, as demonstrated by Raffelsiefen (1999), who found that not even two of the many suffixes of English trigger exactly the same type of morpho-phonological alternations. In other words, in order to really account for the morpho-phonology of English affixes, it seems that we would need as many strata as we have affixes that trigger morpho-phonological alternations, which means that the lexical strata approach cannot be upheld (see also Bauer et al., 2013; Lee-Kim et al., 2013; Plag and Baayen, 2009, for discussion).

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[10] The 27 ms difference for *in-* is computed for the reference level of AFFIX, i.e. negative *in-*. If we compute the difference for locative *in-* we arrive at a somewhat smaller difference of 24 ms. The difference of three milliseconds between the two *in-* prefixes is not significant, as evidenced by the fact that there was no significant interaction of AFFIX and ENVIRONMENT in the model for *in-*.

The second research question was concerned with the potential effect of segmentability on nasal durations. The comparison of the three prefixes revealed that they indeed have different boundary strengths, as measured by four types of indicators: relative frequency, two measures of semantic transparency and the type of base. The most easily segmentable prefix is *un-*, followed by the less segmentable negative *in-*. The least easily segmentable prefix is locative *in-*.

Hay's theory predicts that more easily segmentable prefixes should show longer nasal durations than less easily segmentable prefixes. Thus *un-* should show the longest durations, negative *in-* somewhat shorter durations, and locative *in-* should show the shortest durations. This is exactly what we find in the present data set.

Our study thus replicates analogous effects that were found for other prefixes by Smith et al. (2012). These authors investigated words that featured the prefixes *dis-* and *mis-*. With both prefixes one finds highly transparent words (such as *mistime, mistype, displeased, discolored*) and words that are less transparent (e.g. *mistake, discovered, distorted*). Smith et al. call the fully transparent forms 'prefixed', and the less transparent forms 'pseudo-prefixed'. Their analysis of different phonetic characteristics (duration, formant structures, amplitude, spectral moments) demonstrates two important things. First, the prefixes in the pseudo-prefixed words have shorter durations than in the prefixed words. Second, segments straddling a weaker morphological boundary show phonetic characteristics that are closer to those of morpheme-internal sequences of the same type.

Similar results were also obtained in several studies for the variable darkness of /l/ in English. Abstracting away from differences in certain details, all studies of this phenomenon (i.e. Hayes, 2000; Lee-Kim et al., 2013; Sproat and Fujimura, 1993; Sproat, 1993) find differences in the phonetic implementation according to different degrees of strength of the morphological boundary adjacent to the /l/. For example, in their articulatory study Lee-Kim et al. (2013, 498) find that in words like *droll-est* or *crow-less* "speakers actively utilize tongue body lowering to attain a darker /l/ that signals the morphological boundary". Lee-Kim et al. (2013) also reanalyze data from Sproat and Fujimura (1993) and show that "With a few exceptions, /l/s at a productive morpheme boundary (*kneel-ing*) [. . .] are considerably darker than /l/s in non-productive morpheme boundaries (*tel-ic*) and monomorphemic forms (*Beelik*)" Lee-Kim et al., 2013, 500. The present results concerning the differences between the three prefixes under investigation are thus fully in line with other studies of fine phonetic detail at morphological boundaries of varying strength.

The present study and the ones mentioned in the previous paragraphs have in common that the evidence for an effect of boundary strength on duration is rather indirect. All studies used a categorical difference in boundary strength, as derived on the basis of four segmentability measures in the present study, as expressed by the contrast between pseudo-prefixed and prefixed words (e.g. Smith et al., 2012), or as expressed by the contrast between productive vs. non-productive boundary (e.g. Lee-Kim et al.'s (2013) reinterpretation of Sproat and Fujimura (1993)).

In our study, however, we also tried a different approach by directly testing the effects of individual measures of seg-

mentability, i.e. relative frequency, two measurements of semantic transparency, and type of base. Unexpectedly, in the regression models there were no significant effects of these measurements. This raises the question why the individual segmentability measurements do not show the expected effects.

In general, it seems hard to replicate the phonetic effects of quantitative variables that are supposed to tap into morphological decomposability, as found in Hay's study (2007) of *un-*. Hanique and Ernestus (2012) discuss this problem by comparing a number of studies and come to the conclusion that finding an effect greatly depends on which kind of measure is used. One should also note that finding a significant effect in general greatly depends on sample size. Given the relatively small size of our sample, not finding an effect may simply be due to this property of our data set. Note also that, related to small sample size, there is also the problem that the range of one of our measures, relative frequency, is rather small, which makes it harder to detect potential influences of relative frequency on other variables. Furthermore, we measure only a very small portion of the words in question, instead of larger stretches of sound, for example whole prefixes.

Our data set, originating from natural conversations instead of controlled experiments, has additional limitations emerging from the unbalanced distribution of many variables, which makes it more difficult to detect certain effects. The token-wise distribution of certain measurements may mask the clear differences found in type-based measurements. For example, while the distribution of the semantic transparency measurements by type as shown in Tables 2–4 above show striking differences between prefixes, a token-based analysis yields a less clear picture. For illustration, consider Table 9. While type-wise there is a huge difference between the two *in-* prefixes, there is only a marginal difference token-wise in the distribution of opaque versus transparent forms.

Given that the regression analysis was necessarily token-based it may no longer be surprising that no effect emerged for semantic transparency.

With regard to our semantic transparency measurements, it may be the case that a binary coding that classifies everything as non-transparent that is not fully transparent is perhaps not fine-grained enough to detect more subtle, gradient effects of transparency. However, a more fine-grained rating of morphological complexity does not seem to help much. There is one study (Bürki et al., 2011) that used transparency ratings on a 5-point scale to predict phonetic reduction (of schwa in French) but no effect was found. We used a 4-point scale, to no avail. It thus seems to be possible that such ratings, be they binary or

Table 9

Transparency by prefix (tokens), SEMANTICTRANSPARENCYBINARY.

Transparency (binary)	locative *in-*	negative *in-*
opaque, tokens	42	64
transparent, tokens	29	22
opaque, types	42	7
transparent, types	13	21

Tokens: χ-squared = 3.465, *df* = 1, *p* = 0.063.
Types: χ-squared = 18.173, *df* = 1, *p*-value = 2.017e−05.

Table 10
Summary of dependent variable and predictor variables for *un-*, *N* = 158.

Dependent variable	Mean	St. Dev.	Min	Max
AᴮˢᴼᴸᵁᵀᴇNᴀˢᴀᴸDᵁᴿᴬᵀᴵᴼᴺ	60	28	16	137
Numerical Predictors	Mean	St. Dev.	Min	Max
logRᴇᴸᴬᵀᴵᵛᴇFʀᴇ�QᵁᴇᴺᶜY	−0.797	2.518	−8.495	7.098
SᴇᴹᴬᴺᵀᴵᶜTʀᴬᴺˢᴾᴬʀᴇᴺᶜYRᴬᵀᴵᴺᴳ	1	0	1	1
SᴾᴇᴇᶜʜRᴬᵀᴇ	13.190	2.990	6.136	20.570
Categorical Predictors	Levels			
Eᴺᵛᴵʀᴼᴺᴹᴇᴺᵀ	n#nV: 23	n#C: 68	n#V: 67	
SᵀʀᴇˢˢPᴬᵀᵀᴇʀᴺ	beforeStressed: 102	beforeUnstressed: 56		
SᴇᴹᴬᴺᵀᴵᶜTʀᴬᴺˢᴾᴬʀᴇᴺᶜYBᴵᴺᴬʀY	opaque: 0	transparent: 158		
TYᴾᴇOᶠBᴬˢᴇ	bound root: 2	word: 156		

Table 11
Summary of dependent variable and predictor variables for *in-*, *N* = 156.

Dependent variable	Mean	St. Dev.	Min	Max
AᴮˢᴼᴸᵁᵀᴇNᴀˢᴀᴸDᵁᴿᴬᵀᴵᴼᴺ	76	27	20	170
Numerical Predictors	Mean	St. Dev.	Min	Max
SᴾᴇᴇᶜʜRᴬᵀᴇ	14.290	3.666	5.279	24.320
logRᴇᴸᴬᵀᴵᵛᴇFʀᴇQᵁᴇᴺᶜY	3.599	4.742	−9.670	10.490
SᴇᴹᴬᴺᵀᴵᶜTʀᴬᴺˢᴾᴬʀᴇᴺᶜYRᴬᵀᴵᴺᴳ	2.518	1.108	1	4
Categorical Predictors	Levels			
Eᴺᵛᴵʀᴼᴺᴹᴇᴺᵀ	m#C: 67	m#mV: 89		
Aᶠᶠᴵˣ	inLoc: 70	inNeg: 86		
SᵀʀᴇˢˢPᴬᵀᵀᴇʀᴺ	beforeStressed: 117	beforeUnstressed: 39		
SᴇᴹᴬᴺᵀᴵᶜTʀᴬᴺˢᴾᴬʀᴇᴺᶜYBᴵᴺᴬʀY	opaque: 105	transparent: 51		
TYᴾᴇOᶠBᴬˢᴇ	bound root: 124	word: 32		

on a scale, are not suitable to tap into rather minute differences in the execution of articulatory gestures and the resulting acoustic differences.

Based on our discussion of the lack of phonetic effects emerging with individual measures of morphological decomposability we can state that previous studies either did not include such measures, or, if they did include them, often failed to find the expected effects. In contrast, studies which used holistically defined categories of relative morphological boundary strength (along the lines of 'affix X creates a stronger boundary than affix Y'), including the present one, were able to find phonetic correlates of morphological boundary strength. One reason for this discrepancy might be that the holistic categorization necessarily subsumes all relevant properties of the affixes in question, while individual measurements can only cover single aspects that may contribute to the overall segmentability of a given affix. Future studies will have to clarify this issue.

From a production perspective the systematic phonetic correlates of morphological boundary strength must reflect systematic differences in the planning of speech and thus in the processing of words in production. The present study thus contributes to the growing body of literature that provides empirical evidence that underlying representations cannot be the sole base for articulation. Well-established models of speech production and the mental lexicon seem unable to accomodate this. Levelt et al. (1999, 5), for example, assume that phonological representations are composed of discrete segments and syllables, and the articulator uses pre-programmed gestures stored in a syllabary. Hence, in such feed-forward models morphologically dependent subphonemic detail is not part of these

representations and needs therefore be accounted for by purely phonetic factors that influence articulatory implementation such as speech rate (e.g. Levelt, 1989). Our study, in line with others, demonstrates that such an account is inadequate since on top of the general phonetic influences, one can observe variation depending on morphological structure, for example the strength of a morphological boundary.

An alternative account may be provided by exemplar-based models (e.g. Bybee, 2001; Gahl and Yu, 2006; Goldinger, 1998; Johnson, 2004; Pierrehumbert, 2001, 2002). In such models a lexeme is linked to a frequency distribution over phonetic characteristics, as encountered by a given speaker. These distributions may result in representations that reflect these characteristics (see, for example, Pierrehumbert (2002) for an implementation of the phonetic variability of lexemes). Available exemplar-based approaches have not yet tackled the problem of subtle phonetic differences involved in the differentiation of allegedly homophonous affixes, and it remains to be seen whether this approach will turn out to be able to accommodate the facts.

Table 12
Test statistics for segmentability measurements across the three prefixes.

Segmentability measure	Test statistics	chi-squared	df	*p*-Value
SemanticTransparencyBinary	Chi-square	109.5	2	<2.2e−16
SemanticTransparencyRating	Kruskal–Wallis	136.71	2	<2.2e−16
TypeOfBase	Kruskal–Wallis	108.81	2	<2.2e−16
logRelativeFrequency	Kruskal–Wallis	136.71	2	<2.2e−16

Table 13
Summary of final linear model for variables predicting the Box-Cox-transformed relative duration of [n] in *un*-prefixed words

	Estimate	Std. Error	*t* value	*p*-Value
Intercept	1.029	0.013	80.326	<2e−16
Environment − n#C	−0.072	0.015	−4.858	2.89e−06
Environment − n#V	−0.127	0.015	−8.527	<1.30e−14

Adjusted R-squared: 0.327.

Table 14
Summary of final linear model for variables predicting the Box-Cox-transformed relative duration of [m] in *in*-prefixed words.

	Estimate	Std. Error	*t* value	*p*-value
Intercept	0.987	0.015	65.285	<2e−16
Environment − m#C	0.053	0.007	7.308	1.47e−11
SpeechRate	−0.003	0.001	−3.416	0.001
StressPattern − beforeUnstressed	0.066	0.008	7.876	6.13e−13

Adjusted R-squared: 0.422.

Appendix A

Tables 10, and 11 give an overview of the variables initially included in each model and summarize their distributions.

Appendix B. Statistical tests and regression models

Tables 12–14.

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