Lexical and sublexical effects on the maintenance of contrasts in the lexicon and the paradigm - the case of sound change from MHG to NHG

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Abstract

It has been established that various phonological and phonetic sources affect sound change both on a frequency level and a qualitative level. Simultaneously, drivers of sound change can be lexical and sublexical factors. Previous research, focusing on single phones, has shown that paradigmatic factors tend to influence phonetic properties of sounds, both in synchronic variation as well as diachronic sound change. In this study, we investigate how lexical and paradigmatic predictors have influenced sound change in entire words. Our variable of interest is how many phones have changed in verbs from Middle High German to New High German. We find that a word's similarity with other words, operationalized as mean phonetic distances and the number of phonological neighbors, are significant predictors of the amount of sound change in a word. In addition, we find that sound change depends on two functional references, the lexicon and the respective verbal paradigm. In conclusion, sound change affects entire words and arises from its relation to other words beyond direct phonological neighbors.

keywords: lexicon, paradigm, similarity, sound change

1 Introduction

The sounds of the world's languages are in a constant flux of change. The time range of changes can span between a speaker's life time (Harrington et al., 2000; Beaman and Tomaschek, 2019; Gahl and Baayen, under revision) till several generations (Hay et al., 2015). The current study aims to investigate sound change that happened across several generations. Once a sound change process is terminated – if it ever is –, it seems as though the process was highly regular and can be captured by phonological rules (Kiparsky, 2003). For example, German used to contrast voicing in syllable-final obstruents, but this contrast is lost in the modern language (Iverson and Salmons, 2007), as can be evidenced by morpho-phonological alternations in New German (e.g. [ˈra:t] *wheel* - [ˈrɛ:ɪɔ] *wheels*). However, sound and language change require variation (Wedel, 2006; Winter and Wedel, 2016), which depends on many factors, as studies on phonetic variation in modern languages have shown. Besides social factors (Labov, 2001, 1963), many linguistic factors such as stress, phonetic context, or coarticulation have been identified to be the source for phonetic variation such as the reduction of vowels to schwa or the deletion of segments and syllables (Lieberman, 1963; Öhman, 1966; Magen, 1997; Zimmerer and Reetz, 2011; Zimmerer et al., 2011; Gahl et al., 2012; Zimmerer et al., 2014). In addition, lexical factors such as a word's frequency of occurrence or its phonological neighborhood density, have been found to correlate with phonetic variation¹. In the present study,

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¹The definition of *lexical factors* used in this study is in accordance with definitions found in current quantitative studies. We acknowledge that in the traditional phonological view, the examples used here do not necessarily classify as lexical.

we aim to investigate these lexical factors correlate with sound change between Middle High German and New High German in entire words. Changes in a language’s sound system can be split into two categories. On the one hand, there are processes that change the phonetic quality of a sound, such as vowel shifts (Hay et al., 2015), mergers (Wedel et al., 2013b,a) and the many possibilities of consonant changes, among others devoicing, palatalization or sibilantization (Padgett and Żygis, 2007). On the other hand, there are deletion processes where single segments or even entire syllables are eliminated (Rickard, 2003; Zimmerer and Reetz, 2011; Bybee, 2017).

In the remainder of the introduction, we will first discuss in detail the relation between lexical factors and phonetic variation in modern languages, and relate them to historical sound change. After presenting the hypotheses of this study, – i.e. that similarity to other words is a source of sound change – we present Middle High German and how its phonetic system was different in relation to New High German. Subsequently, we present the results of our analysis in which we used Supervised Components Generalized Linear Regression (Bry et al., 2013) and Generalized Additive Models (Wood, 2011) to predict the mount of change between the two language stages.

1.1 Lexical factors in phonetic variation

Abundant studies find that spectro-temporal characteristics of segments are stronger acoustically reduced – reflected by more centralized vowels and shorter segments – and the probability of segment deletion is greater in more frequent words than in less frequent words (Whalen, 1991; Jurafsky et al., 2001; Aylett and Turk, 2004, 2006; Gahl, 2008; Bybee, 2002, 2017). Similar effects are reported for segmental frequencies (Cohen Priva, 2015).

Frequency of occurrence is obtained for each segment or word form individually, and therefore considers a single unit independently from other units. One might therefore erroneously assume that words and segments are separated from other words and segments in the mental lexicon. However, similar changes in terms of spectro-temporal reduction are observed when larger chunks of words and segments are taken into account such as frequencies of occurrence of larger word sequences (Tremblay and Baayen, 2010) or conditional probabilities (Gregory et al., 1999; Bell et al., 2009; Seyfarth, 2014; Cohen Priva, 2015), i.e. a word’s or segment’s probability of occurrence given their context. Such findings indicate that words and segments are not independent from each other but form complex networks in the mental lexicon, in which words and segments are related to other words and segments. These assumptions have already been supported by early priming studies (see e.g. Humphreys et al., 1982; Luce et al., 2000)². The most common interpretation of this phenomenon is that more frequent and more probable words given their context convey less information due to their greater a priori expectancy and are consequently reduced (Aylett and Turk, 2004; Jaeger, 2010). Less frequent words convey

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²A note on conditional probability. Current theories of learning regard the brain as an apparatus which discriminates visual and acoustic cues to predict upcoming events (Ramscar et al., 2010, 2013, 2017). Any correlation between conditional probability and cognitive behavior such as acoustic characteristics or response times can therefore be interpreted to indicate that the brain is predicting upcoming events given previous events. This indicates that there is a relation among independent words, albeit in a temporal order.

more information and therefore need to be less reduced.

In addition to sequential order and expectancy, word forms can be related by the sharing a set of segments. The German minimal pair [ˈmaʊs] *mouse* and [ˈhaʊs] *house* is one example of shared segments. In the following study, we will call relations between word forms *lexical* relations, and relations on the basis of segments *sublexical* relations (following Tomaschek et al.).

One popular possibility to assess sublexical relations is the phonological neighborhood density (PND), i.e. a value which indicates for a given word the number of words that can be created by adding, changing or deleting one segment in the given word (Vitevitch and Luce, 1999). The relation between phonological neighborhood density and acoustic characteristics is paradox. On the one hand, shorter acoustic duration of whole words (Gahl et al., 2012; Gahl and Strand, 2016) are reported for words with greater phonological density (concomittant with faster production latencies (Vitevitch, 2002)), indicating acoustic reduction. From a lexical perspective, articulatory gestures can be regarded as better practiced in words with more phonological neighbors due to their greater cumulative frequency of occurrence, allowing faster speech production (for effects of frequency of occurrence on articulatory gestures, see Tomaschek et al. (2018c,a)). On the other hand, vowels in words of greater phonological neighborhood density have been shown to be longer and more dispersed (see Scarborough (2003); Munson and Solomon (2004); Munson (2007) for vowels, see Goldrick et al. (2013) for stop consonant articulation). To name an example English minimal pairs such as *pill* and *bill*. The onset plosives in these words are pronounced with more extreme voice onset times than the plosive in words that lack a minimal pair counterpart, such as *pipe* – as there is no *bipe* (Goldrick et al., 2013; Wedel et al., 2018). These findings can be explained by joining phonetic contrasts to lexical meanings. Take as an example the German words [haus], [raʊs], [maʊs], [aus]. These four words are contrasted only by their onset consonant. Wedel and colleagues (Wedel et al., 2013b,a) argue that phones in words with more phonological neighbors, as is the case for [-aus] in our examples, help to discriminate lots of lexical meanings³. In order to make the phonetic signal less confusable with other words, i.e. in order to increase its discriminability, the phonetic characteristics of all phones are enhanced. By contrast, words with a small number of phonological neighbors, such as [eːləfənt], are relatively less confusable with other words, therefore need less discriminable phonetic characteristics. Using an exemplar based simulation, Winter and Wedel (2016) illustrated how phonetic cues for individual segments become more constrained, i.e. more separated and therefore more discriminable, when the number of words increases which have to be discriminated. To conclude, the research on phonological neighborhood density – a measure of sublexical relations among words – indicates that a word’s phonetic characteristics are enhanced when it is very similar to other words, thus decreasing the risk of lexical confusion. In the framework of discriminative learning, greater similarity with words and thus greater lexical confusion, is equivalent to greater *uncertainty* about the lexical meaning. Enhancing phonetic characteristics would therefore increase a word’s *discriminability* Ramscar et al. (2010, 2013). We will adopt this terminology in the present paper. Wedel and colleagues refer to this as *functional load* Hockett (1967), i.e. the “degree to which a sound contributes to word distinctions” (Wedel et al., 2013b,a; Winter and Wedel, 2016).

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³In the terminology of discriminative learning, these are semantic contrasts

1.2 Lexical factors in sound change

In addition to well established phonetic factors affecting sound change (Harrington et al., 2008; Kleber et al., 2012; Ohala, 1989; Garrett and Johnson, 2013; Ohala, 1993a,b; Hale, 2003; Donegan and Nathan, 2015; Grosvald and Corina, 2012; Blevins, 2015), recent studies have shown that lexical predictors such as frequency of occurrence and phonological neighborhood density, too, are predictive of sound change. Like phonological neighborhood density for speech production, it has been observed that frequency of occurrence has a paradoxical role in phonetic variation and sound change. On the one hand, greater frequency of occurrence is correlated with a higher deletion probability, i.e. a reduction of the speech signal. For example, Bybee (2002) observed greater probability of [t, d] deletion in high frequency words than in low frequency words (see also Aylett and Turk (2006); Cohen Priva (2015); Jurafsky et al. (2001); Bell et al. (2009) for similar effects). On the other hand, Hay et al. (2015), who investigated the New Zealand vowel shift in data spanning 130 years, reported that the shift emerged in low-frequency words first, while high-frequency words maintained older vocalic variants. It seems as though frequency of occurrence can function as a driver of sound change, through reduction. Simultaneously, it constitutes an anchor for older forms, which is probably due to greater practice with articulatory gestures in high frequency words, which result in stronger articulatory representations that are less affected by changes in the sound system (Tomaschek et al., 2018a,c). This assumption is supported by irregular verbs, which are among the most frequent words in many languages' lexicons (Blevins et al., 2015). To say it in Bybee's (Bybee, 2002, , 263) own words, "[reductive] sound change tends to affect high frequency words before low-frequency words, but analogical leveling or regularization tends to affect low-frequency words before high-frequency words". However, this statement misses that sound change can result in homophones increasing uncertainty about lexical meanings. And indeed, sound change is modulated by whether or not potential homophones are created, as has been shown by Wedel et al. (2013b), who extended their considerations beyond simple deletion processes and focused on how sound change shapes phonological systems. They investigated mergers of contrastive phones in eight languages (e.g AE [p] vs. [b] as in *pit* vs. *bit*). Unsurprisingly, they found that a word's frequency of occurrence was positively correlated with a greater probability of a merger. In other words, the contrast was reduced in words with a greater a priori expectancy.

Wedel and colleagues also found effects of sublexical relations onto sound change. The probability of a merger was modulated by whether or not a word had a minimal pair: phones in words that had a minimal pair were less probable to be merged with a contrastive phone than phones in words which actually had a minimal pair. The probability of merger was smaller for words with a larger number of minimal pairs. Likewise, Blevins and Wedel (2009) showed that the probability of sound change is smaller if the result would be homophony. Thus, if the uncertainty about the lexical meaning was increased because the word had a higher similarity with other words, the contrastive phones were not merged, maintaining the discriminability of the signal.

The question about the paradoxical role of frequency of occurrence and how it interacts with the discriminability of the signal remains unsolved. This question was attacked just recently by Todd et al. (2019). In most studies on sound change, speakers were regarded as the source of sound change, as they change the acoustic signal. Following a suggestion

by Ohala (1981), Todd et al. (2019) focused on the role of the listener and the *rate* of sound change. Using an Exemplar-based model simulation, they found that sound change evolves at different rates depending on how it affects the discriminability of the word and the amount of uncertainty it creates about lexical meanings. When the sound change does not change the amount of uncertainty of lexical meaning in a word, high and low frequency words change at the same rate. When sound change decreases uncertainty, then low-frequency words change at a higher rate than high-frequency words. When sound change increases uncertainty, then high-frequency words change at a higher rate than low-frequency words. The latter is possible because high frequency words have a greater a priori expectancy and can be effectively recognized in context (Ernestus et al., 2002). Todd et al. (2019) investigated sound change of two contrastive phones. The question therefore arises to what extent this interaction between uncertainty and word frequency can be observed for whole words.

However, sound change not only relies on global considerations but seems to be modulated by an interaction between lexical and sublexical relations. Wedel et al. (2013a) found that the number of minimal pairs based on lemma and syntactic category were a better predictor of mergers than minimal pairs on the basis of word forms. Thus, not only do phonological relations between words affect sound change, but also their functional relations in the grammar of a language. To a certain degree, this has already been reported by Bybee (2002) for phonetic variation in modern languages. Word final [t, d] in past verbs are stronger prone to deletion than in other word classes of American English. Bybee argues that this effect is mediated by the phonetic context in which past verbs occur in contrast to other words (see also Bybee, 2017, for more support of this kind). While her argumentation might be valid for past verbs in English, there is additional evidence for effects of functional and lexical relations onto phonetic variation. For example, Bell et al. (2009) show that the duration of function and content words show different patterns of correlations with frequency of occurrence and conditional probabilities. Drager (2011) shows systematic variation in duration of the American English word ‘like’ depending on the word’s grammatical category as does Lohmann (2017) for homophonous noun-verb pairs in American English. Again, not only the lexical relations are involved but also the sublexical. Studies by Smith et al. (2012); Ben Hedia and Plag (2017); Plag et al. (2017); Plag and Ben Hedia (2017); Smith et al. (2012); Lee-Kim et al. (2013) show that phones show systematic differences in duration depending on which morphological contrast they encode. To name one example, word final [s] in American English words is longest when it is non-morphemic, of intermediate duration when the [s] is a suffix (plural) and shortest when it is a clitic (genitive) (Plag et al., 2017; Tomaschek et al.). Moreover, there is evidence that paradigmatic relations, several studies show that even a higher level of functional abstraction, matter for phonetic variation of modern languages, too. For example, the duration of third person singular [s] in English (Cohen, 2014a) and the duration of Dutch interfixes (Kuperman et al., 2007) correlate with paradigmatic probabilities, i.e. the probability of a word within its paradigm. Russian vowels show enhanced phonetic characteristics in proportion to paradigmatic support (Cohen, 2014b, 2015). Finally, a word’s duration in Estonian is shorter, when it is part of a larger inflectional paradigm and part of a larger morphological family (Loo et al. (2017b), and see also Loo et al. (2017a) for effects in lexical decision). Thus, morphological and paradigmatic relations modulate the degree of phonetic enhancement, on top of relation to the

remaining lexicon. The question arises to what extent these effects – found in modern languages – can be found to affect sound change.

1.3 The present study

Taken together, numerous studies show that frequency of occurrence, phonological neighborhood density, and morphological and paradigmatic relations systematically modulate synchronic phonetic variation. Having established that frequency of occurrence and phonological neighborhood density have effects on historical sound change, the question therefore arises to what extent this is also true for paradigmatic relations. To investigate this question, we analyzed how verbs have changed between the language stage of Middle High German to the language stage of New High German, and operationalized paradigmatic relations by contrasting effects of the verbal paradigm with effects of the remaining lexicon.

Studies on phonetic variation and sound change usually focus on a single segment in words while ignoring simultaneous changes to other segments in the same word. Given the amount of changes a language experiences (from single sounds to the deletion of entire syllables), it is more than likely that several segments have changed between two language stages. Thus, whereas previous studies were concerned with the discriminability of phonological systems (Hockett, 1967; Wedel et al., 2013b,a; Winter and Wedel, 2016), we are concerned with the discriminability of and uncertainty in the entire lexicon. We therefore investigated the amount of sound changes in the word as a whole.

We obtained measures for Middle High German verb forms, i.e. for the time point where the sound change potentially started. We furthermore investigated both processes that result in ‘language change’. First, we inspect how strongly New High German (NHG) words diverge from their Middle High German (MHG) form. Second, we inspect how strongly MHG words got reduced on their journey to NHG words.

We expected to observe stronger change and reduction between the MHG and NHG for MHG words of greater frequency of occurrence and of smaller phonological neighborhood density, which we used as a ersatz-measure for minimal pairs. The management of discriminability and uncertainty of words in relation to their paradigm should be of larger importance than in relation to the rest of the lexicon. We therefore expected to observe stronger change in correlation with measures which were obtained on the basis of a verbal paradigm rather than the entire lexicon.

2 Methods and material

2.1 Description of Middle High German

In the following section, we first describe the older language stage of German, before presenting our word material. The medieval language of Middle High German (MHG) is a cluster of German regional varieties spoken in the high and late middle ages in what is today the southern part of Germany, Switzerland and Austria (Wells, 1990, p. 105ff.). It is usually dated from 1050 to 1350, directly following the oldest attested language stage of Old High German. In contrast to Old High German, MHG is better attested with corpora often being almost 10 times larger in terms of token count than those of Old

High German. MHG is old enough to provide a possibility to analyze a 900 to 600-year difference to the modern language stage of German. Crucially, although NHG is allocated mainly to Northern Germany while MHG is allocated to Southern Germany, it is still possible to compare MHG with NHG because NHG is the direct genetic descendant of the MHG dialects (e.g. Salmons, 2012; Harbert, 2007). Unlike NHG, MHG had no supra-regional standard language and the single attestations are rather momentary captures of the regional variety the authors chose for their literary work. The comparison between MHG and NHG on a segmental basis is nevertheless valid since most MHG varieties differ in sounds which fall later together in one sound in standard NHG. For example, diphthongization (e.g. OHG, early MHG /uo/ > NHG [u:]) was unequally distributed since some dialects retained the original monophthong longer than others. This example marks a difference *between* varieties of MHG, but since they fall together in one standard NHG descendant, the number of changes stays the same in different dialects

In other instances where the aforementioned case did not apply, we find some dialects of the same language stage that are more different from standard NHG in some respects than others. E.g. the MHG voiceless stop /t/ could occur voiced between vowels in the Bavarian variety of MHG. However, we expect that the large amount of data provides a representative average where single deviations are accounted for. The same is true for author- and scribe-related variation. Individual idiosyncrasies are leveled to an average among the numerous other texts.

Sound changes between Middle High German and New High German affected predominantly the vocalic system (Wells, 1990). Long tense vowels were diphthongized ([i:, y:, u:] > [ai, oi au]). Diphthongs became long tense vowels ([iə, uo, yə] > [i:, u:, y:]). Short lax vowels in open syllables became long tense vowels ([a, ɔ, ʏ, ɪ] > [a:, o:, y:, i:], ([e, ɛ, æ] > [e:])). As for the consonants, the two fricatives [ʒ] and [s] merged to [s]. Furthermore, [s] evolved to [ʃ] preceding liquids and nasals. In addition, reduction processes caused the deletion of unstressed schwas, a process which still can be observed in NHG, as well (Zimmerer et al., 2014). The MHG corpus we used for the current investigation contains texts from the 10th to 15th century, with a vast majority falling into the classic MHG period between the 11th and the 14th century. The appendix provides additional information on the corpus.

2.2 Material and variables

We decided to focus only on verbs (which we will call from now on *words* for the sake of convenience). Investigating more than one functional class would potentially create the risk of mixing and confusing different operating processes proper to the respective class. To operationalize the phonetic change between MHG and NHG, we used two dependent variables in the current study. The first is *MHG To NHG Replacement*, calculated by the Levenshtein distance of the phonetic transcription between a verb form in MHG and NHG. This measure ignores whether sounds were added or deleted from MHG to NHG. This is why we used a second dependent variable of interest, *MHG To NHG Difference*, the difference in number of segments in MHG and NHG. To our surprise, phones not only were deleted between MHG and NHG, but also added. Take MHG [altən] vs. NHG [altərn] (*to get older*) and MHG [axtənt] vs. NHG axtən (*they respect*) as an example. Both have *MHG To NHG Replacement* of 1. The first has *MHG To NHG Difference* of

+1 as the [r] was added, the second has *MHG To NHG Difference* of -1 as the final [t] was deleted. *MHG To NHG Replacement* ranges between 0 and 6, *MHG To NHG Difference* ranges between -5 and $+5$.

In the following, we describe the predictors used in the current study. Lexical measures for Middle High German (MHG) were based on the Klein et al. (2016) corpus (description in the Appendix); those for New High German (NHG) were based on the SDEWAC and CELEX corpora (Baayen et al., 1993; Faaß and Eckart, 2013; Shaoul et al., 2014).

We used a word form’s lexical frequency of occurrence in MHG (*Word Frequency*). Furthermore, we gauged the number of phones (*Number Phones*) for each word. For MHG, the measure was obtained on the basis of quasi phonetic transcriptions, which we created automatically from the orthographic form. For NHG, it was calculated on the basis of the phonetic transcription of the verb forms in the CELEX corpus. Frequency of occurrence is correlated with the number of phones a word has (Zipf, 1935). However, their effects might differ, as the larger the number of phones in a word, the greater is the probability of sound changes.

To examine the effects of the lexicon independently from paradigmatic effects, we calculated two sets of measures. The first set took into account only word forms in the verbal paradigm (variable names will be suffixed with *Paradigm*). The second set took into account the remaining lexicon used in the current study, excluding the word forms in the verbal paradigm (suffixed with *Lexicon*). We calculated two measures of phonological neighborhood density and mean phonological distances for each MHG and NHG verb (appropriately prefixed).

We operationalized sublexical relations among words by means of a word form’s phonological neighborhood density (*PND*) that is defined by the number of instances created by replacing, adding or subtracting one single phone (i.e. Levenshtein distance = 1). For example, the NHG verb form [gʊ] “go, 3rd person singular indicative past” has, among others, the phonological neighbors [gʊə] “go, 3rd person singular conjunctive present” and [ge:ɪ] “go, 3rd person plural indicative present”. Phonological neighborhood density operationalizes the number of instances which diverge from a word form with the Levenshtein distance of 1. However, its application to verbal paradigms may be problematic, because verbs usually vary at more than two positions due to morpho-phonological processes. For example, [gʊst] is based on the same stem as [gʊ] and has the Levenshtein distance of 2. It would therefore not count as a phonological neighbor. Nevertheless, the stem in both forms is clearly phonologically identical. In addition, phonological neighborhood density ignores relations to words beyond the direct phonological neighborhood.

This situation is schematically illustrated in Figure 1. For a given word, the phonological distance, or dissimilarity to other words in the paradigm can be located on the x-axis, the difference to other words in the remaining lexicon can be located on the y-axis. The dotted diagonal represents the boundary between these two spaces. The dashed bold line represents all neighbors with a Levenshtein distance of 1. However, the lexicon consists of words that differ by more than one phone from a given word. The more those words differ from a given word, the farther they are located on the x-axis or on the y-axis. To assess the distance of a given word from those words, i.e. those that are not located in the direct phonological neighborhood of a given word, we propose the measure *mean phonological distance* (*MPD*). MPD is calculated by summing up a word form’s Levenshtein distances to all words (in the paradigm or the remaining lexicon) and dividing the sum

Figure 1: *Schematic illustration of a word's relation to other words.*

by the number of instances in the respective condition.⁴

To conclude, PND assesses on the number of similar words for a given word. MPD assesses the similarity/dissimilarity of a given word with with respect to the entire lexicon. Both assess the uncertainty about the lexical meaning, only from two different perspectives. Given the way these two measures are calculated, they are inversely proportional to each other. A word with a large PND and a smaller MPD has a greater probability to be confused with other words – it is less similar – and therefore has a greater uncertainty about the lexical meaning it encodes. A word with a small PND and a large MPD has a smaller probability of being confused with other words – it is more similar – and therefore has a smaller uncertainty about the lexical meaning it encodes.

In total, we used six MHG predictors in the current analysis: *MHG Word Frequency*, *MHG Number Phones*, *MHG PND Paradigm*, *MHG PND Lexicon*, *MHG MPD Paradigm*,

⁴Similar to the *PhonLev* measure in Tucker et al. (2019)

357 *MHG MPD Lexicon.*

358 We also obtained the same measures for New High German (NHG): *NHG Word*
359 *Frequency*, *NHG Number Phones*, *NHG PND Paradigm*, *NHG PND Lexicon*, *NHG MPD*
360 *Paradigm*, *NHG MPD Lexicon*. Although these measures are not the primary target of
361 the current study, they will be used as dependent variables to allow us to assess how these
362 measures have changed between MHG and NHG, and therefore showing a more coherent
363 picture of sound change by broadening the spectrum of potential interactions.

364 We excluded the lemmas NHG ‘haben’ and NHG ‘mögen’ as visual inspection indi-
365 cated that they were erroneously mismatched between NHG and MHG. The final number
366 of tokens in this study was 15668 verb forms. Non-normally distributed variables were
367 log-transformed or square rooted in order to minimize the overly strong influence of out-
368 liers⁵.

369 The problems we want to assess are:

370 (1) How does phonetic similarity on a sublexical level influence sound change? We hy-
371 pothesized that an increased similarity disfavors the occurrence sound change (see e.g.
372 Wedel et al., 2013b,a). (2) How strong does the similarity towards a word’s paradigm and
373 the entire lexicon affect sound change regarding? We hypothesize that the same amount
374 of similarity within the paradigm should have a stronger effect as the same amount of
375 similarity to the remaining lexicon, as discrimination within the paradigm should be
376 maintained. (3) How strong is the influence of word frequency on the effects mentioned
377 in (1) and (2)? We hypothesized that high frequency favors reductions since more fre-
378 quent words seem to have a greater probability to lose segments than rare words (e.g.
379 Whalen, 1991; Aylett and Turk, 2006; Gahl, 2008; Bybee, 2002, 2017).

380 **3 Analysis and Results**

381 **3.1 Separate neighborhood densities for the paradigm and the** 382 **rest of the lexicon**

383 We first inspected whether the use of *Phonological Neighborhood Density* and *Mean*
384 *Phonological Distance* in MHG calculated separately on the basis of the paradigm and
385 on the basis of the remaining lexicon was justified, rather than using measures on the
386 basis of the entire lexicon. We fitted four separate generalized linear models (family =
387 ‘poisson’) to *MHG To NHG Change*, once with the separated measures, once with the
388 measures on the basis of the entire lexicon. For both, phonological neighborhood den-
389 sity and mean phonological distance, model comparison on the basis of AIC indicated
390 that the separated measures provided a better fit to the model (AIC reduction of 141.88
391 and of 892.56, respectively). We therefore conclude that the use of separate measures is
392 justified.

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⁵Detailed information can be found in the supplementary materials.

3.2 Correlation between all dependent and all independent variables

In our first analysis, we used Supervised Components Generalized Linear Regression (SCGLR, Version 2.0.3, Bry et al., 2013). There are two reasons why we selected this technique. First, our predictors are potentially strongly correlated and SCGLR is capable of managing collinearity among predictors. SCGLR is based on Standard Principal Component Regression (PCA), a method that reduces the amount of collinear variables by orthogonalization and dimensionality reduction, which can subsequently be used in a standard regression analysis. However, in standard PCA, the variance of the dependent variable and its correlation with the predictors is not taken into account during orthogonalization. This can lead to false-positive interpretations⁶.

Furthermore, SCGLR allows to fit a model with multiple dependent variables. This allows us not only to investigate how the six MHG predictors are correlated with the amount of change between MHG and NHG (i.e. by using the variables *MHG To NHG Change* and *MHG To NHG Difference* as a dependent variable). Moreover, we can simultaneously investigate how these MHG predictors are correlated with the entire set of lexical and sublexical measures for NHG. In this way, SCGLR we can investigate the process of language change and its effects onto the current stage of the language as a whole.

We used the SCGLR approach as a tool for an exploratory analysis in which we are able to capture how predictors and dependent variables related to each other. This is why we wanted to keep the complexity of this analysis as low as possible, fitting only on two supervised components to the data. Given that *MHG To NHG Difference* ranges between negative and positive values, i.e. indicates deletion and addition of phones between MHG and NHG, we have not included it into this analysis, as a proper interpretation of the effect was not possible.

3.2.1 Model description

Table 1 shows the γ values, i.e. the β equivalents of the dependent variables in SCGLR, for the first and the second supervised component⁷. This table serves as the validation of the significance of the effects discussed below. It informs us that supervised component 1 and 2 are significantly predictive for all dependent variables apart from one, namely *NHG MPD Lexicon*.

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⁶Consider the following example with two correlated variables, A and B . It is possible that A is significantly correlated with the dependent variable while B is not (Tomaschek et al., 2018b). If both are mapped onto the same principle component, the principal component will be significantly correlated with the dependent variable. Erroneously, a false-positive effect of B would be assumed. To overcome this shortcoming, orthogonalization in SCGLR is performed by taking into account the variance and the collinearity of both, dependent variable and predictors. For more details on how to perform an SCGLR analysis, see Tomaschek et al. (2018b).

⁷Supervised components include the influence of the response, i.e. they are not exogenous. Significance of the effects, i.e. predictive strength of the supervised components on the dependent variables, had to be assessed by fitting the SCGLR model to 9 parts of the data. The predictors in the remaining 1 part of the data were orthogonalized using the eigenvalues obtained in the SCGLR model and then subsequently fitted to each dependent variable in a standard linear regression analysis from which the p-values for the estimates in the SCGLR analysis were obtained (personal communication by Xavier Bry).

Table 1: Estimates for the supervised components and the dependent variables.

	dependent variable	estimate	standard error	t-value	p-value
(Intercept)	NHG Word Frequency	2.05	0.08	26.13	<0.001
sc1	NHG Word Frequency	0.29	0.03	8.55	<0.001
sc2	NHG Word Frequency	-0.29	0.05	-5.51	<0.001
(Intercept)	NHG Number Phones	1.89	0.01	256.14	<0.001
sc1	NHG Number Phones	-0.12	0.00	-35.78	<0.001
sc2	NHG Number Phones	0.03	0.01	5.96	<0.001
(Intercept)	NHG PND Paradigm	5.00	0.06	88.86	<0.001
sc1	NHG PND Paradigm	0.58	0.02	23.62	<0.001
sc2	NHG PND Paradigm	-0.99	0.04	-26.44	<0.001
(Intercept)	NHG MPD Paradigm	-0.30	0.03	-12.13	<0.001
sc1	NHG MPD Paradigm	0.26	0.01	23.27	<0.001
sc2	NHG MPD Paradigm	-0.53	0.02	-31.35	<0.001
(Intercept)	NHG PND Lexicon	0.96	0.05	19.67	<0.001
sc1	NHG PND Lexicon	0.60	0.02	28.25	<0.001
sc2	NHG PND Lexicon	-0.11	0.03	-3.46	0.001
(Intercept)	NHG MPD Lexicon	0.73	0.03	27.36	<0.001
sc1	NHG MPD Lexicon	-0.46	0.01	-39.98	<0.001
sc2	NHG MPD Lexicon	0.04	0.02	2.18	0.029
(Intercept)	MHG To NHG Change	2.94	0.04	68.89	<0.001
sc1	MHG To NHG Change	-0.34	0.02	-18.49	<0.001
sc2	MHG To NHG Change	-0.41	0.03	-14.42	<0.001

3.2.2 Overview of the plot

Figure 2: *SCGLR* correlation plot between the lexical measures for NHG (as predictors, in black), the for MHG (as dependent variables, in blue) and the supervised components 1 and 2 (*x*, *y*-axis).

Figure 2 illustrates the results of the SCGLR analysis by means of a correlation plot. Most of the variance in the entire data is explained by supervised component 1 (x-axis, 45.87%); supervised component 2 (y-axis) explained 18.46%. In total, the two supervised components explained 63.8% of the variance in the data. Arrows represent dependent variables (in blue) and independent variables (in black). Supervised components 1 and 2 are depicted at the x-axis and y-axis, respectively. For example, *MHG To NHG Change* points to the left bottom corner. It is located in the negative-negative quadrant, indicating that it has a negative correlation with both supervised components. By contrast, *MHG PND Paradigm* is located in the positive-positive quadrant, indicating that it has a positive correlation with both supervised components. The length of the arrow repre-

sents the summed correlation of a variable between the two supervised components. The longer, the stronger the correlation. What is more important is the orientation of the arrows (i.e. predictors) relatively to each other. Arrows pointing in the same direction indicate positive correlations between the variables. Arrows pointing in opposite directions indicate negative correlations. Arrows orthogonal to each other indicate no correlation. In the following paragraphs, we will inspect these correlations in more detail. To increase the readability of the plot, we split predictor and dependent variables in the first two panels. The right most panel illustrates all of them together.

3.2.3 Correlations among MHG predictors

We first inspect the correlations among the Middle High German (MHG) predictors in Figure 2 (a). We observe that *MHG Number Phones* and *MHG MPD Lexicon* are positively correlated, as indicated by their pointing into the same direction. Thus, longer words are more different from the words in the remaining lexicon. We further observe that *MHG Word Frequency* and *MHG PND Lexicon* also show a positive correlation. This is not surprising, as it known that more frequent words tend to have more phonological neighbors (Frauenfelder et al., 1993). Simultaneously, these two predictors show a strong negative correlation with *MHG Number Phones* and *MHG MPD Lexicon*, indicating that the more frequent MHG words were shorter. This as has already been pointed out by Zipf (1935) for modern languages and has repeatedly been replicated ever since. Also, *MHG MPD Lexicon* and *MHG Word Frequency* are negatively correlated. Thus, frequent words are more dissimilar from words of the entire lexicon, supporting the finding that more frequent words maintain more irregular forms (Blevins et al., 2015).

Note that *MHG PND Paradigm* is positively correlated with *MHG PND Lexicon*, indicating that words which have a large number of neighbors in the paradigm tend to have a large number of neighbors in the remaining lexicon. *MHG MPD Paradigm* and *MHG MPD Lexicon* are orthogonal to each other, indicating that they have independent effects onto our dependent variables of interest, further supporting the division of these sublexical measures. In other words: paradigm and the remaining lexicon have independent effects on sound change.

3.2.4 Correlations among NHG dependent variables

We now turn our attention to the correlations among the dependent variables in Figure 2 (b). We first focus onto the lexical and sublexical variables for New High German (NHG), ignoring the changes between MHG and NHG. Like in MHG, we observe a positive correlation between *NHG Number Phones* and *NHG MPD Lexicon*. Comparing these two NHG variables with the equivalent MHG variables indicates that they are positively correlated with the MHG predictors. We also observe a negative correlation between *NHG Number Phones* / *NHG MPD Lexicon* and *NHG PND Lexicon* / *NHG Word Frequency*. This means that longer words in MHG remained longer in NHG, more frequent words in MHG remained more frequent in NHG, words with more phonological neighbors in MHG still have more phonological neighbors in NHG. Although this finding could be considered as trivial, it indicates that we are still dealing with the a similar language system. Otherwise the equivalent variables in MHG and NHG should be either less or not at all correlated.

We turn our attention to the details of phonological neighborhood and distance within the paradigm. In MHG, *MHG PND Paradigm* and *MHG MPD Paradigm* were slightly negatively correlated, i.e. words with more phonological neighbors in the paradigm tended to be more similar with words in the paradigm. By contrast, in NHG, *NHG PND Paradigm* and *NHG MPD Paradigm* show a strong positive correlation, i.e. words with more phonological neighbors are more dissimilar with words in the paradigm. This change indicates an entire reorganization of the phonetic contrasts within the paradigm, while the words' relation to the remaining lexicon remained stable, as indicated by the positive correlation between *MHG MPD Lexicon* and *MHG PND Lexicon*. Potential explanation of these changes might be differences in the stem and differences in the suffixation in MHG and NHG. Given the focus of the current paper on the change between MHG and NHG, rather than in changes in the discriminative systems, investigating this effect is postponed to future research.

3.2.5 Amount of change between MHG and NHG

In the following paragraph, we turn our attention to the correlations between the predictors in MHG and the amount of change between MHG and NHG, as illustrated in Figure 2 (c).

MHG To NHG Change has a slightly negative correlation with *MHG Word Frequency*, hence, more frequent words tended to change less than rare words⁸. Word frequency seems to have functioned as an anchor for older word forms, as postulated by Hay et al. (2015), and contradicting the findings of Wedel et al. (2013b) that phonetic contrasts get lost in more frequent words. However, given the length of the arrow of *MHG Word Frequency*, and given the almost orthogonal angle between *MHG Word Frequency* and *MHG To NHG Change*, frequency of occurrence is a very weak predictor of change between MHG and NHG. Rather, phonological neighborhood density and mean phonological distance, i.e. sublexical relations rather than lexical, are better predictors of change between MHG and NHG. We observe a positive correlation between *MHG To NHG Change*, *MHG MPD Lexicon* and *MHG MPD Paradigm*. This positive correlation indicates that more dissimilar MHG words were changed stronger between MHG and NHG, both in the paradigm and in the rest of the lexicon. By contrast, when a high degree of similarity already existed, words changed little. The number of the direct phonological neighbors influences sound change, too, as indicated by the negative correlation of *MHG To NHG Change* with *MHG PND Paradigm* and *MHG PND Lexicon*. Words surrounded by lots of similar words were changed less between MHG and NHG. This result parallels the positive correlation of *MHG MPD Paradigm* and *MHG MPD Lexicon*. We observe that more dissimilar words in MHG remained more dissimilar in NHG, as evidenced by the positive correlation between *MHG MPD Paradigm* and *NHG MPD Paradigm*. Words thus maintained their discriminability with respect to other words in the paradigm.

Furthermore, we observe that MHG words which had a large number of phonological neighbors in MHG in the rest of the lexicon are less similar to the remaining lexicon in NHG, as evidenced by a strong negative correlation between *MHG PND Lexicon* with *NHG MPD Lexicon*. One possible explanation is that words which had a high probability

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⁸For the sake of simplicity, the 'average number of change in a word' will be referred to as 'the amount of change' in the remainder of the manuscript.

of being confused with the remaining lexicon in MHG (as changing only one segment is a small discriminable cue) became less confusable in NHG.

In spite of its power to investigate complex correlation structures in the data, Supervised Components Generalized Linear Regression (SCGLR) does not provide any information about the size of the changes. In addition, SCGLR does not allow to test interactions, which is why we will apply Generalized Additive Models to investigate the data following two sections. Furthermore, so far we have focused only on sound change processes and have ignored reduction processes. In the following section, we turn our attention to investigate how much, on average, did words get changed between MHG and NHG and how strongly this change correlated with reduction processes.

3.3 Investigating average amount of sound change

Wedel et al. (2013b) and Wedel et al. (2013a) reported that merger probability is proportional to word frequency and that the strength of the effect was smaller when words had a phonological neighbor. Although the effect of word frequency attested in the present study was positive rather than negative, we tested this prediction. We investigated the interaction between word frequency and phonological neighborhood density using a Generalized Additive Mixed-Effects Model (GAMs Wood, 2006, 2011, 2013). GAMs allow to model non-linear functional relations between a response and one covariate by means of smooths, and non-linear functional relations between a response and two or more covariates with tensor products. For a detailed description of GAMs, see Tomaschek et al. (2014); Wieling et al. (2016); Tomaschek et al. (2018a,c) and their application to articulatory data.

We first discuss our model strategy before presenting the results. Our basic model regressed *MHG To NHG Change* against smooths (i.e. a non-linear relation with one predictor, using $s()$) for *MHG Word Frequency*, *MHG PND Paradigm*, *MHG PND Lexicon*, *MHG MPD Paradigm*, *MHG MPD Lexicon*. We did not include *MHG Number Phones* due to strong collinearity with *MHG Word Frequency*. Table 2 shows that all smooths show significant non-linear relations with *MHG To NHG Change*, as is indicated by larger degrees of freedom ('edf') than 1 and p-values below 0.001⁹.

We tested how frequency of occurrence and phonological neighborhood density affected sound change with two partial tensor smooths, i.e. non-linear interaction between two variables, using $ti()$ ¹⁰ fitting an interaction between *MHG Word Frequency* and *MHG PND Paradigm*, and between *MHG Word Frequency* and *MHG PND Lexicon*. As can be seen at the bottom of Table 2, these interactions were not significant. In other words, our data did not support the above stated hypothesis. We therefore turned our attention in an exploratory analysis to an interaction between the lexical and sublexical measures for the lexicon and the paradigm, to investigate how the paradigm and the remaining lexicon influence sound change jointly. We included two partial interactions to the model: *MHG*

⁹Note that model summaries for GAMS lack an estimated β coefficient. The strength and direction of the effect is inferred from the plots.

¹⁰The split into smooths using $s()$ and partial interactions using $ti()$ is equivalent to a split of an interaction in a linear regression model such as $Y \sim X * Z$ into $Y \sim X + Z + X : Z$. This separation allows to inspect whether main effects and interactions significantly correlate independently with the response variables.

PND Paradigm $\times$ *MHG PND Lexicon* and *MHG MPD Paradigm* $\times$ *MHG MPD Lexicon*. Both interactions turned out to be significant. However, visual inspection of the *MHG PND Paradigm* $\times$ *MHG PND Lexicon* interaction showed that the effects were located at the very edges of the predictor space, while the majority of the predictor space did not yield any effect. This is why it was excluded from the model term. The second interaction, by contrast, was kept (see Table 2) and its inclusion significantly improved the model fit, as found by means of a χ^2 -test ($\chi^2_{17,20} = 46.7$, $p < 0.001$, van Rij et al. (2015)).

Table 2: GAM summary table fitting *MHG To NHG Change*. $s()$ terms represent smooths, fitting a non-linear relationship with the dependent variable and one independent variable; $ti()$ terms represent partial tensor smooths, fitting a non-linear interaction between two predictors. P-values < 0.05 indicate non-linear relationship between predictors and dependent variable.

	edf	Ref.df	Chi.sq	p-value
$s(\text{MHG Word Frequency})$	2.31	2.64	14.58	< 0.001
$s(\text{MHG PND Paradigm})$	1.00	1.00	45.67	< 0.001
$s(\text{MHG PND Lexicon})$	2.43	2.74	21.32	< 0.001
$s(\text{MHG MPD Paradigm})$	2.93	2.99	618.68	< 0.001
$s(\text{MHG MPD Lexicon})$	2.56	2.85	138.32	< 0.001
$ti(\text{MHG MPD Paradigm}, \text{MHG MPD Lexicon})$	6.30	7.42	112.40	< 0.001
$ti(\text{MHG Word Frequency}, \text{MHG PND Lexicon})$	1.00	1.00	0.06	0.81
$ti(\text{MHG Word Frequency}, \text{MHG PND Paradigm})$	1.97	2.52	3.85	0.21

Figure 3 (a) illustrates the significant estimated effects of the model presented in Table 2. As indicated in Figure 2, *MHG Word Frequency* is correlated negatively with *MHG To NHG Change* for a minority of mid frequency words. For all other frequencies of occurrences, no correlation can be attested, as evidenced by the horizontal smooth line in low frequency words and large confidence interval in high frequency words. This finding supports our conclusion in the previous section that word frequency is not a good predictor for change between MHG and NHG. Rather, sublexical predictors drive the change. We observe that both measures of phonological neighborhood density, *MHG PND Paradigm* and *MHG PND Lexicon* (Figure 3, b&c), show negative correlations with *MHG To NHG Change*, replicating the finding in Figure 2.

We have hypothesized that the uncertainty management in terms of similarity between words is more important within the paradigm than towards the remaining lexicon, as sound changes within the paradigm, which might result in the collapse of contrasts, increase the uncertainty about the lexical meaning stronger than sound changes with respect to the remaining lexicon. This prediction is supported by a stronger and more consistent effect of *MHG PND Paradigm* than of *MHG PND Lexicon*. When the effect size of these two predictors is tested against each other by keeping one of the predictors in the model while excluding the other one, *MHG MPD Paradigm* yields a higher R^2 than *MHG MPD Lexicon* (24.9% vs. 22%), while providing a better model fit, as indicated by a lower ML score for the *MHG PND Paradigm* (ML difference of 203.4).

As we have argued above, phonological neighborhood density takes into account only the direct phonological neighbors (where greater values are proportional to a greater probability of confusion) whereas mean phonological distance assesses the similarity to all words (where greater values are proportional to a smaller probability of confusion). Figure 3 (d) illustrates the interaction between these two predictors. The amount of change is encoded by the contour lines and the colors, with bright yellow colors representing a large amount of change and dark blue colors represent a small amount of change. Replicating

Figure 3: *Estimated effects of lexical and sublexical MHG predictors on the amount of change between MHG and NHG. Plots a) to c) show the effects of the smooths. The dashed horizontal line represents the model's intercept. The grey solid lines represent the distribution. Plot d) shows the final estimated effects of the interaction. The color encodes the predicted effect: blue encodes small amount, green middle amount, yellow a high amount of change. White spaces indicate missing data.*

the findings in Figure 2, we observe that more dissimilar words, both within the paradigm (x-axis) and to other words in the lexicon (y-axis), were stronger changed between MHG and NHG. *MHG MPD Paradigm* and *MHG MPD Lexicon* interact insofar as the amount of change across *MHG MPD Paradigm* is stronger for low *MHG MPD Lexicon* values and weaker for high *MHG MPD Lexicon* values. The same is true from the perspective of *MHG MPD Lexicon*. Crucially, words which are very similar to other words in the paradigm as well as to in the lexicon were not changed at all.

3.4 Investigating average amount of sound deletion/addition

Table 3: GAM summary table fitting *MHG To NHG Difference*. $s()$ terms represent smooths, fitting a non-linear relationship with the dependent variable; $ti()$ terms represent partial tensor smooths, fitting a non-linear interaction between two predictors. P-values < 0.05 indicate non-linear relationship between predictors and dependent variable.

	edf	Ref.df	Chi.sq	p-value
$s(\text{MHG Word Frequency})$	2.69	2.87	22.96	< 0.001
$s(\text{MHG PND Lexicon})$	2.88	2.98	43.35	< 0.001
$s(\text{MHG PND Paradigm})$	2.85	2.95	18.92	< 0.001
$s(\text{MHG MPD Lexicon})$	2.88	2.98	27.70	< 0.001
$s(\text{MHG MPD Paradigm})$	2.95	2.99	36.81	< 0.001
$s(\text{MHG To NHG Change})$	2.36	2.61	2.53	0.04
$ti(\text{MHG Word Frequency}, \text{MHG To NHG Change})$	5.39	6.24	17.37	< 0.001
$ti(\text{MHG PND Paradigm}, \text{MHG PND Lexicon})$	4.36	5.18	9.96	< 0.001
$ti(\text{MHG MPD Paradigm}, \text{MHG MPD Lexicon})$	6.49	7.45	8.98	< 0.001
$ti(\text{MHG Word Frequency}, \text{MHG PND Paradigm})$	4.22	4.84	9.67	< 0.001
$ti(\text{MHG Word Frequency}, \text{MHG PND Lexicon})$	1.18	1.33	7.25	0.01

Figure 4: *Estimated effects of lexical and sublexical MHG predictors on the change in number of segments between MHG and NHG. The color encodes the predicted effect: blue encodes a strong negative effect, green indicates a small effect, yellow a strong positive effect. White spaces indicate missing data. Note that z-scales differ across the panels.*

To investigate under which conditions phones were deleted or added to MHG words, we fitted *MHG To NHG Difference* with smooths for *MHG Word Frequency*, *MHG PND Paradigm*, *MHG PND Lexicon*, *MHG MPD Paradigm*, *MHG MPD Lexicon* as well as *MHG To NHG Change*. Table 3 shows that all of the predictors have a significant non-linear relationship with *MHG To NHG Difference*. We furthermore added five interactions to the model, where *MHG Word Frequency* interacted with each of the other predictors.

No other interactions were tested. All of the interactions turned out to be significant. Given the high Pearson’s product moment correlation between *MHG PND Lexicon* and *MHG MPD Lexicon* ($R = -0.62$), we tested for effects of collinearity in the model, but none were observed (Tomaschek et al., 2018b).

We first evaluated how the amount of reduction/addition was related to an interaction between frequency of occurrence and the amount of change between MHG and NHG (Figure 4, a). Darker blue colors encode reduction between MHG and NHG, brighter yellow colors encode addition between MHG and NHG. When words were changed, as indicated by greater values of *MHG To NHG Change*, we observe that *MHG Word Frequency* (x-axis) is positively correlated with *MHG To NHG Difference*. Rare words in MHG were stronger reduced than more frequent words (*MHG Word Frequency* < 2). For a minority of high frequency words, we even observe addition. Similarly to the effects on the amount of change, this finding is contrary to the general finding that more frequent words get reduced (Bybee, 2017; Wedel et al., 2013b; Jurafsky et al., 2002; Bell et al., 2009; Aylett and Turk, 2004).

Figure 4 (b) illustrates the significant interaction between *MHG Word Frequency* (x-axis) and *MHG PND Lexicon*. The effect of *MHG Word Frequency* is modulated insofar as segments were deleted in rare MHG words which had a small and medium number of phonological neighbors in the lexicon (y-axis). Segments were added to frequent words and those with a large number of phonological neighbors (larger than 3.5). By contrast, the effect of phonological neighborhood density is reversed, when the paradigm is taken into account (Figure 4, c). MHG Words with more phonological neighbors in the paradigm lost more segments than words with less phonological neighbors (y-axis), and the effect is stronger for mid frequency words than for low frequency words.

In the following paragraph, we investigate how the sublexical measures for the paradigm and the lexicon interacted with respect to the reduction/addition of segments to MHG words. The positive correlation between *MHG PND Lexicon* (y-axis) and *MHG To NHG Difference* is modulated by *MHG PND Paradigm* (x-axis in Figure 4, d). On average, fewer segments were deleted and more phones were added to words with a small number of phonological neighbors in the paradigm, than to words with a medium number of phonological paradigm, as evidenced by more green and yellow colors for low values of *MHG PND Paradigm* and more blue colors for medium values of *MHG PND Paradigm*. For words with higher numbers of phonological neighbors in the paradigm, the effect is attenuated, probably due to sparse data. These findings supports our earlier hypothesis that similarity regarding the lexicon or paradigm both have an independent effect on the occurrence of sound change.

The finding indicates that when the probability of confusion is smaller (as indexed by smaller PND), a reduction of the words discriminability, as evidenced by the deletion of segments, is possible. This is somewhat in line with our previous hypothesis that a decrease in similarity might reduce the probability of change. When the probability of confusion increases, new segments are added. This pattern is mirrored by the interaction between the phonological density predictors, *MHG MPD Paradigm* and *MHG MPD Lexicon* (Figure 4, e), albeit they do not exhibit any addition effects. The effect of *MHG MPD Paradigm* is modulated by *MHG MPD Lexicon*. For low and high values of *MHG MPD Lexicon*, the effect of *MHG MPD Paradigm* is inversely u-shaped with a peak around -1, for mean values of *MHG MPD Lexicon* the effect of *MHG MPD Paradigm* is rather in-

creasing from -3 to 1 and then decreasing. Thus, the smaller a word’s mean phonological distance in the paradigm, i.e. the larger its probability of confusion with other words, the stronger it got reduced.

MHG MPD Lexicon has an inversely u-shaped effect onto *MHG To NHG Difference*. In its center, the smallest reduction effects can be observed (illustrated by bright yellow colors), which increases towards its edges (illustrated by green and blue colors). Given the current data it is not possible why *MHG MPD Lexicon* exhibits such a pattern.

4 Discussion

Wedel and colleagues (Wedel et al., 2013b,a) have shown that the probability of a merger between two contrasting phones, i.e. the reduction of a phonetic contrast, is smaller in words which are less frequent and which have phonological neighbors, than in words which are more frequent and which do not have phonological neighbors. Wedel and colleagues interpreted these results from the perspective of ‘functional load’ (Hockett, 1967). They argue that words containing phones with greater functional load i.e. the degree with which a phone discriminates among possible lexical meanings, would undergo less phonetic merger than vice versa. We operationalized amount of change as the number of changed and deleted phones in verbs in Middle High German (MHG) and New High German (NHG). To obtain a measurement of how a given word relates to other words, we used two kinds of measures. First, we counted the number of direct phonological neighbors, i.e. the phonological neighborhood density. This measure follows from Wedel and colleagues use of minimal pairs. Second, we assessed the degree of difference between a given word and all other words, obtaining the *mean phonological distance*. Both measures gauge a word’s amount of similarity to and probability of confusion with other words.

We found similarity among words and probabilities of confusion affect not only a language’s phonological system and the degree to which its phones are contrasted (Wedel et al., 2013b,a; Winter and Wedel, 2016), but also hold words as discriminative units. In this sense, the findings by Wedel and colleagues that phonetic contrasts do or do not collapse could be regarded as a sub-processes affecting the entire word. In addition, the larger a word’s similarity to other words, the larger is the risk that a sound change potentially creates homophonous word forms. Consequently, our findings support the idea that words with a greater phonological neighborhood density undergo less sound change in order to lower the risk of collapsing contrasts, as has been argued by (Blevins, 2015).

Crucially, we show that the phonology of a word is not only related to its direct neighbors, as postulated by Wedel et al., but simultaneously to all other words in the lexicon. Rather than being an independent abstract units in the mental lexicon Chomsky and Halle (1968), our result supports the idea that a word is a member a complex network on the basis of lexical and sublexical relations. It is within this network that the word has to maintain its discriminability, i.e. its capability to discriminate a certain lexical meaning from other lexical meanings. The strength of these lexical and sublexical relations, has repeatedly been shown to correlate with production and processing characteristics in modern languages, affecting the discriminability of the words (Tremblay and Baayen, 2010; Bell et al., 2009; Seyfarth, 2014; Cohen Priva, 2015; Scarborough, 2003; Munson

and Solomon, 2004; Munson, 2007; Goldrick et al., 2013). This kind of variation observed in modern language can be regarded as the origins for future sound change.

Following the findings in previous studies (Wedel et al., 2013b,a; Bybee, 2002; Aylett and Turk, 2004), we expected that sound change and phonetic reduction would be stronger in frequent words than in rare words. However, word frequency was predictive only for a small portion of very high frequency words, and in that case more frequent words experienced less change. Furthermore, frequent words showed less reduction than rare words. Our findings, thus, support the idea that word frequency can function as an driver of reduction processes in the phonological system (Wedel et al., 2013b,a; Bybee, 2002), but it functions as an anchor for words as a hole within the entire lexical system. One possible explanation is that frequent words have a stronger entrenchment within the mental lexicon which makes them less prone to change and reduction (Tomaschek et al., 2018c,a). For example, Hay et al. (2015) has shown that vowel shifts are less probable in high frequency words than in low frequency words. Beaman and Tomaschek (2019) have shown the same for diphthong mergers in Swabian. Another possible explanation, especially for the different effect of reduction, might be rooted in perceptual processes. Words with the same amount of canonical phones have been shown to be perceived as having more independent phones when their phonological neighborhood density is large than when their phonological neighborhood density is small (Benkí, 2003). When the input is larger, the output has to be larger, and vice versa. One particular interesting finding is that words of very high frequency were actually added phones. It is possible that these verbs experienced analogical levelling Garrett (2015) such that irregular past verbs were made more regular. However, details of why this might be the case is left for future studies.

In the current study, we focused on words as isolated, stand-alone units. However, studies on modern languages indicate that a given word’s phonetic variation correlates with its relation to its context. Concretely, more probable words in a context are stronger reduced than less probable words (Gregory et al., 1999; Bell et al., 2009; Seyfarth, 2014). Given that word sequences, i.e. higher level lexical relations, affect phonetic variation in modern language, we hypothesize that a word’s contextual relations will affect sound change, too. We find support for this hypothesis from studies which show that the probability of meaning change correlates with a word’s semantic density, a measure which is obtained on the basis of entire sentences or paragraphs (Landauer and Dumais, 2008; Sagi et al., 2009; Dubossarsky et al., 2016; Tang, 2018). We further could hypothesize that a word’s semantic density will also correlate with the amount of sound change.

(Wedel et al., 2013a) were able to show that constraining the lexical and sublexical network to a word’s grammatical function explains a larger proportion of sound change than if unconstrained relationships are assumed. In our study, we have constrained the sublexical relations to the paradigm and contrasted them to relations with the remaining lexicon. This separation provided a better predictor for sound change than an aggregated predictor, indicating that functional relations among words have an important effect on sound change. Our results show that the language systems tries to maintain a grater amount of discriminability between words of the same or similar semantics, i.e. within a paradigm, than to words of different semantics. This notion is supported by findings which show that that morphological category and paradigmatic relations correlate with phonetic variation in modern languages (Kuperman et al., 2007; Cohen, 2014a,b, 2015;

Loo et al., 2017b; Smith et al., 2012; Ben Hedia and Plag, 2017; Plag et al., 2017; Plag and Ben Hedia, 2017; Smith et al., 2012; Lee-Kim et al., 2013; Lohmann, 2017).

We close this discussion by linking our results to current findings in discriminative learning which use learning algorithms such as the Naïve Discriminative Learner (NDL). NDL is a two-layer network which takes lexical and sublexical relations into account to learn to discriminate lexical meanings, such as [haus], [raus], [maus], [aus], on the basis of their diphone (or triphone) cues such as #h, ha, #r, ra, #m, ma, #a, au, us, u#. Crucially, NDL assumes that all sublexical cues are related to all lexical meanings in the lexicon. In interaction with frequency of occurrence, these sublexical relations result in cue competition which modulates how strongly underlying cues support a specific lexical meaning. From the strength of the cue support for lexical meanings, systematic differences in cognitive processing costs can be predicted (e.g. Baayen et al., 2011, 2013; Baayen and Ramscar, 2015; Arnold et al., 2017). To name a concrete example, Tomaschek et al. applied NDL measures to predict acoustic characteristics of word-final [s] in American English. They found that a stronger bottom-up support from [s] cues to a morphological contrast, i.e. how well these cues discriminated a word’s morphological function, is associated with longer, less reduced word final [s] durations in American English. This finding mirrors the current results that there is less reduction in words of stronger a priori expectancy. Future studies of sound change should therefore rely on naive discriminative learning, which allows to directly gauge a word’s similarity to the entire network and therefore provides a measure of discriminability in a more direct way.

5 Conclusion

In this study it could be shown that there is indeed evidence for the motivation of sound change by the paradigm and the entire lexicon and several underlying processes could be identified. Overall it has become clear that two of the most influential factors are the similarity or dissimilarity between the particular verb and other verbs in its lemma and between the verb and all verbs in the language. These two instances, the paradigm and the entire lexicon, prove to be two frames of reference – two centers of gravity that influence sound change independently of each other in relation to how similar or dissimilar the respective words are to them. Sound change occurs as a function of where the respective word is positioned relative to these two frames of reference. A major stabilizing factor is the neighborhood density which slows change processes down. As those categories are solely morphological, the explanation of sound change as being also induced by dissimilarity from the paradigm could be confirmed. Therefore, the introduction of the new variable of the mean distance has proven to be effective in describing and predicting sound change.

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7 Appendix: Creation of the Digital German Diachronic Verb Corpus

The corpus we used for the study Klein et al. (2016) is a collection of 394 annotated MHG texts from the years 1050-1350. As preparation, we parsed the online accessible MHG dictionary by Gerhard Köbler Köbler (2014) to be able to add the translation to the words from the text corpus. The website was copied and stored to a text-file, which was then read line-by-line. From each line, the tokens denoting the MHG lemma and its translation were extracted and stored separately.

Concerning the MHG corpus, the data provided by Klein et al. (2016) were originally in xml format, so we automatically went through each file using a parser function which extracted each word token and each specification about the token. The extracted categories were token ID (*ID*), word in normalized spelling (*norm*), the lemma (*lemma*), the lemma with segmentation and stress (*lemma_gen*), part of speech of the word-form (*pos*), part of speech of the lemma (*pos_gen*), inflection of the word-form (*infl*), the word-form's inflection class (*inflClass*), the lemma's inflection class (*inflClass_gen*). After that, the translation of each word was added by comparing every MHG verb with the verbs in the aforementioned dictionary. For words contained in the dictionary, the translation was automatically added. For those lemmas in the corpus where no exact match could be found in the dictionary, the corpus verb with the least Levenshtein distance was selected to provide the translation. After finishing this process, a .csv file was created which was then manually edited to control for errors that could have occurred in the step before. Those translations which were false were corrected on a random basis i.e. not the entire corpus was checked but randomly chosen sections were checked. The next step was to standardize the annotations in the corpus which were unequal to those provided in the CELEX. Therefore, the annotations for *pos*, *pos_gen*, *infl*, *inflClass*, *inflClass_gen* were transformed to adhere to the CELEX conventions. Thereafter, the MHG verbs were transformed to meet the phonetic segment convention of CELEX. Note, that some sounds not contained in NHG (such as the diphthong *uo*) were converted by being assigned random, previously unused symbols and letters. After the extraction, the entries were stripped from brackets and diacritics. In a next step, the distance of each verb to other verbs in the corpus were computed as mean distance and as neighborhood density both to all other verbs in the corpus and to other forms in the lemma and stored as two additional columns. Further, the CELEX verb lemmas were added based on the above generated translations of the MHG verb lemmas and the particular forms were selected by congruence of CELEX inflection annotation and the MHG corpus' inflection annotation. Similarly to the MHG verbs, the distances of NHG verbs to the corpus and to the lemma were computed and added. Lastly, the segment number of each verb (both MHG and NHG) was added and all numeric variables were z-scaled. Moreover, the neighborhood densities, the mean Levenshtein distances were log-transformed.

Subsequently, a phonetic transcription for each verb was automatically generated based on the conversion of orthography to phonetics using the knowledge of MHG phonology (see e.g. Klein et al. (2018)) by converting known consonant and vowel combinations of normalized MHG orthography into a machine-readable phonetic representation. E.g. the grapheme combination <ph> in MHG stands for [pf]. Since all word tokens in the corpus are given in normalized MHG orthography as a result of a critical edition, we had

826 to rely on converting orthography to be able to compare the phonetics of MHG words
827 to their NHG reflexes. Additionally, the transcriptions of the New High German equiva-
828 lents from the CELEX corpus in the edit of Shaoul and Tomaschek (2013); Baayen et al.
829 (1993); Faaß and Eckart (2013) were added (**Transcription NHG**) and matched to the
830 Middle High German verbs based on **verb**. Note that the Middle High German verbs
831 were matched to their NHG reflexes by genetic consistency, hence semantic changes were
832 ignored.

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