Rhythmic structure effects on glottalisation: A study of different speech styles in Polish and German

“But the increasing interest in connected, more specifically spontaneous speech data bases has made it mandatory for researchers to enter into phonetics and phonology above the word in real-life communication, and it is in this domain that glottalisation phenomena abound.” (Kohler 2001: 317)

Abstract: The present paper examines glottal stops and the glottalisation of word-initial vowels in Polish and German. The presence of glottal marking is studied depending on speech style (‘speech’ vs. ‘dialogue’), prominence, phrasal position, speech rate, word type, preceding segment, and following vowel height. A question is also posed about the extent to which glottal marking might be dependent on the rhythmic structure of a given language or style. We analyzed recordings of 18 Polish and German speakers. The results point to significant differences between the two languages. In German, glottal marking occurs significantly more often (63.4%) than in Polish (45%). Whereas in both languages (and both styles) the majority of prominent vowels are more often glottally marked than non-prominent vowels, in German word-initial non-prominent syllables are also marked relatively often. Regarding phrase position, glottal marking occurs significantly more often at the phrase-initial position compared to phrase-medial position in Polish, while no such difference has been found in German. In addition, it is shown that in both languages glottal marking is strongly dependent on the tongue height of the marked vowel: low vowels are more frequently glottalised than non-low vowels. Finally, glottal marking in Polish is more likely to occur when rhythmic variability shifts towards the ‘indeterminate’, strengthening the hypothesis that glottal marking facilitates perceptual grouping.
1 Introduction

The glottal stop is in a sense a unique sound, as it is not only part of phonemic systems (of 35.58% of the world’s languages included in the P-base; Mielke 2007) and an allophone in other languages but especially because it serves prosodic functions in typologically unrelated languages, e.g., American English (Dilley, Shattuck-Hufnagel, and Ostendorf 1996), Czech and Spanish (Bissiri et al. 2011), German (Kohler 1994), Polish (Żygis and Pompino-Marschall 2012), and others. It is precisely this latter type of behaviour that is difficult to capture, mainly because it may be influenced by several factors, and at the same time, it is also subject to a huge inter- and intra-speaker variability, not to mention cross-linguistic differences (see, e.g., Umeda 1978; Dilley, Shattuck-Hufnagel, and Ostendorf 1996; Redi and Shattuck-Hufnagel 2001; Huffman 2005; Garellek 2012). Nevertheless, thanks to previous studies, we are at least able to classify different types of glottalisation phenomena and hypothesize what parameters create favorable conditions for the appearance of a glottal stop (and glottalisation).

Kohler (2001: 282) proposed four different types of glottalisation, linking them to different functions:

1. Vowel-related glottalisation phenomena, which signal the boundaries of words or morphemes.
2. Plosive-related glottalisation phenomena, which occur as reinforcement or even replacement of plosives.
3. Syllable-related glottalisation phenomena, which characterize syllable types along a scale from a glottal stop to glottalisation (e.g., Danish stød).
4. Utterance-related glottalisation phenomena, which comprise (i) phrase-final relaxation of phonation and (ii) truncation, i.e., utterance-internal tensing of phonation.

The present paper focuses on vowel-related glottalisation phenomena (cf. 1. above) that are found in the word-initial position. As previous studies have shown, their appearance is a complex phenomenon related to various parameters. Whereas earlier studies have pointed to speech rate, discourse type, word type, stress, word frequency, the quality of the following vowel, or grammatical difficulty as determining factors (see, e.g., Krech 1968; Umeda 1978), advances in prosodic phonology have made it possible to provide a link between glottal marking and boundaries of various prosodic constituents (see, e.g., Pierrehumbert

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1 The P-base (Mielke 2007) comprises 548 languages of the world, out of which 195 (35.58%) include the glottal stop /ʔ/ as a part of their phonetic systems.
1994; Redi and Shuttuck-Hufnagel 2001). Another striking observation from earlier studies on glottal marking is that they focused on glottal stops, leaving aside glottalisation or even condemning it as ‘pathological’ (Krech 1968). More recent studies, however, rehabilitated glottalisation deeming it a useful source of information and finding that it is even the most frequent realization of a canonical glottal stop (see Kohler 1994; Rodgers 1999).

Looking at the parameters influencing glottal marking, it appears to be undeniable that stressed syllables favour the presence of glottal stops/glottalisation in comparison to unstressed ones (Umeda 1978; Kohler 1994; Dilley, Shattuck-Hufnagel, and Ostendorf 1996; Rodgers 1999). Glottal marking has also been found to be speech rate-dependent in the sense that slow speech rate induces a higher percentage of glottal stops than high speech rate (Umeda 1978) but higher speech rate is characterized by more glottalisation (Rodgers 1999). Prosodic phrase boundary is another factor determining the presence of glottal marking: full intonational phrase boundaries exhibit glottal marking more frequently than intermediate intonational phrase boundaries (Dilley, Shattuck-Hufnagel, and Ostendorf 1996). Furthermore, read speech is found to have more glottal stops than glottalisation, which in turn is more often found in casual speech (Rodgers 1999). Another factor that determines glottal marking is pitch accent: pitch accented vowels are more often glottalised in comparison to those which do not bear pitch accent (Dilley, Shattuck-Hufnagel, and Ostendorf 1996). Finally, glottal marking appears to be dependent on word category: lexical words are more often glottally marked than function words (Umeda 1978; Rodgers 1999).

The aforementioned results, however, are based on the investigation of German and English. Thus, we need to include other languages in a thorough investigation not only for comparison reasons, but also for understanding the different mechanisms that languages may use in the process of marking prosodic boundaries (cf. Matoušek and Kala [2005] for an investigation of the Czech glottal stop). Furthermore, it is not clear – since, to the best of our knowledge, the link between rhythmic structure and glottal marking has not yet been investigated in English or German – if and to what extent rhythm may have impact on the appearance of glottal stop/glottalisation in a given language. Thus, it remains to be seen why some parameters, including rhythm, are better predictors for glottal marking than others from a cross-linguistic perspective.

The present study is aimed at investigating glottal marking of word boundaries in two languages: German and Polish. The comparison may be insightful in that German and Polish are very similar regarding the status of the glottal stop but differ from each other as far as the stress system and rhythmic structure are concerned. The glottal stop is neither part of the phonemic system nor an allophone in either language but it is found in fluent Polish and German. However,
whereas the German stress system is complex and stress is not fixed, Polish stress is predictable and systematically falls on the penultimate syllable. Furthermore, it is widely agreed that German is a stress-timed language, while there is no consensus in the literature concerning how Polish should be classified in a stress typology; see Section 2.2 for details.

Thus, the main purpose of the study is to investigate the differences in glottal marking of vowel-initial words in German and Polish by taking into consideration various parameters such as rhythmic structure, discourse type (speech vs. dialogue), speech rate, phrase position (phrase initial vs. phrase-medial), word type (lexical vs. function words), prominence (prominent vs. non-prominent syllable), preceding segment (vowel vs. consonant), and vowel height of the word-initial vowel (low vs. mid vs. high vowels). The overarching goal of the study is to investigate the interaction of the segmental (glottalisation/glottal stop, vowel height) with the supra-segmental level (word stress, rhythmic structure, phrasal position).

The paper is organized as follows. Section 2 presents previous phonetic and phonological studies on glottal stops and glottalisation in German and Polish and describes some prosodic characteristics of both languages. Section 3 presents the experimental design of the acoustic study, and Section 4 provides its results. Section 5 discusses differences between the results found for the two languages and their possible explanation, and concludes the paper.

2 Previous studies

2.1 Glottal stop and glottalisation in German and Polish

In Polish and German, the two languages examined here, the glottal stop is not part of the phonemic inventory (cf. Wiese [2000: 16] for German and Dukiewicz [1995: 25] for Polish). In both languages glottalisation/glottal stop insertion is referred to as an optional rule applying on the surface representation, though in slightly different contexts.

In German, a glottal stop is argued to optionally appear at the beginning of a vowel-initial prosodic foot. Examples are provided in (1) (Hall 1992: 58–59; cf. also Wiese 2000).

(1) a. /aʳm/ ['aʳm] or ['ʔaʳm] ‘poor’
b. /ɔft/ ['ɔft] or ['ʔɔft] ‘often’
c. /te.a.te/ [te. 'a.te] or [te.ʔa:.te] ‘theatre’
d. /mu.ze.um/ [mu.'ze.um] but *[mu. 'ze.ʔum] ‘museum’
Alber's (2001) analysis of morphological boundaries in Standard German leads her to conclude that a glottal stop is found in two contexts: (i) at the left edge of a vowel-initial stressed syllable and (ii) at the left edge of a vowel-initial root or prefix. Alber (2001: 6) also notices an influence of stress on the presence of glottal stop “though it is less clear whether the difference between stressed and unstressed syllables is strong enough to be integrated into a phonological analysis.”

Besides phonologically oriented studies, there are a number of phonetic studies on glottal marking in German including Krech (1968), Kohler (1994, 2001), and Rodgers (1999). Krech (1968), who based her analysis on perceptual impression, found that after a pause both stressed and unstressed syllables are marked by a glottal stop, while in a sequence of words the glottal stop is found more frequently in a stressed syllable. Another finding relevant for the present study was that the glottal stop appears much more often in words with the initial /a/ than in words starting with /i/ and /u/.

Kohler’s (1994) corpus-based study focuses on glottal marking of morphological junctures, including word-internal boundaries, and glottal stops as the realization of various stops, e.g., Freita[k]abend > Freitaʔ[ʔ]abend, ‘Friday evening’. Among various conclusions, the most relevant one for the present study seems to be that postpausal position and stressed syllables favour glottal marking. Kohler (1994) has also shown that the preceding segment, i.e., the final segment of the preceding word, may influence the glottal marking in the sense that the plosive context shows the largest proportion of glottal stops before stressed and unstressed vowels in comparison to other environments.

Rodgers (1999) found that glottal stops appear more often in read speech than in spontaneous speech, in contrast to glottalisation which shows the opposite distribution. Furthermore, the glottal stop is found more often in phrase-initial than phrase-final position, whereas glottalisation is most frequent phrase-medially. Rodgers also reports that lexical words are produced with more glottal stops in comparison to function words. Finally, regarding sentence accent, accented vowels are more often glottally marked than unaccented ones.

Glottal stops and glottalisation in Polish have been given very little attention in the literature. Rubach (2000), who analysed the phonological behaviour of glottal stops in Slavic languages, provides examples for Polish such as Adam to zrobil? ‘Adam did it?’ where the first vowel in Adam is pronounced with a glottal stop, and Nie! ‘no!’ where the glottal stop appears in the coda position [ɲɛʔ]. In conclusion, Rubach (2000: 292) states, “I have no analysis for this data, but the descriptive facts are clear: a glottal stop is an emphasis marker.”

Dukiewicz (1995: 25) provides three different contexts in which glottal marking can occur in Polish, i.e., at a word-initial vocalic boundary, especially in a post-pausal position (cf. 2a), in a word-medial position, mostly at prefix-stem
boundaries (cf. 2b, 2c), or in vowels pronounced in isolation (cf. 2d; Dukiewicz 1995: 45). (The examples without glottal stops were added by the authors of the present paper).

(2) a. /u.+kut͡ɕ/ [u.kut͡ɕ] or [ʔu.kut͡ɕ] ‘to forge’ (perfective)
   b. /na.uka/ [na.uka] or [na.ʔuka] ‘science’
   c. /na.+u.ʈ͡ʂat͡ɕ/ [na. ‘u.ʈ͡ʂat͡ɕ] or [na. ‘ʔu.ʈ͡ʂat͡ɕ] ‘to teach’ (perfective)
   d. /ɔ/ [ɔ] or [ʔɔʔ] ‘about’

Kraska-Szlenk (2003: 70) also notes that an optional glottal stop that appears at prefix-stem boundaries helps to preserve a contrast between minimal pairs as in, e.g., pod-eduk-ow-ač [pɔd.ʔedukowat͡ɕ] ‘to educate (a little)’ and po-deduk-ow-ač [pɔ.педεdukowat͡ɕ] ‘to deduce (a little)’ (cf. Rubach and Booij 1990).

Furthermore, Kraska-Szlenk and Żygis (2012), who investigated the phonetic realization of prefix-stem boundaries in Polish complex words, conclude that a glottal stop is one of a few acoustic cues found at prefix and vowel-initial stem boundaries and its appearance depends on the frequency of a given word. The boundary in frequent words is considerably less marked, i.e., produced with no or fewer acoustic cues than the boundary in infrequent or rare words, which is frequently realized with glottal stops and/or glottalisation, among other markers.

In summary, previous studies on Polish glottal marking are either descriptive or their scope is limited to a particular morphologically oriented research question. In the present study we aim at changing the perspective by studying data gained from different speech styles and analyzing glottal marking by taking into consideration a spectrum of various parameters, as listed in the Introduction.

2.2 Rhythmic structure of German and Polish

Descriptions of Polish rhythmic strategies found in the literature are often impressionistic or inconclusive. Primarily for this reason, the present study involves an independent analysis of rhythmic structures in Polish and German. Also, we introduce a discourse variable in the form of two very different speech styles ('prepared' speeches and spontaneous dialogues) that additionally warrants a direct rhythm analysis. The methods chosen to characterise rhythmic structure as a variable that might influence glottalisation rate are described in Section 3.1.3. First, we sketch the rhythmic characteristics of both German and Polish by considering literature on rhythmic types. We also look at speech tempo and the respective stress and prominence systems.
2.2.1 Rhythm type

Within the space of canonical rhythm types, Polish has been placed between stress- (Rubach and Booij 1985) and syllable-timing (Hayes and Puppel 1985) and, consequently, is often described as ‘mixed’ (Nespor 1990). Certainly, some phonological characteristics suggested to correlate with distinct rhythm types (Dauer 1983) point to a mixed type for Polish: large consonant clusters and no vowel reduction. Regarding the former, however, frequencies of complex syllable types in Polish were found to be rather low: relatively simple syllables (CV, CCV, CVC, CCVC) predominated in a large corpus analysed by Klessa (2006). Regarding the latter, phonetic vowel reduction ranging from centralisation to deletion was observed by Rubach (1974) and, especially for unstressed high vowels, by Sawicka (1995). Nowak (2006) demonstrated the applicability of the target undershoot model (Lindblom 1963) to the variability of Polish vowels, especially in the context of consonants with a palatal component (‘soft’ consonants). In general, however, Polish seems to exhibit a “limited durational variation of […] vowels vis-à-vis many other languages”, as reiterated by Nowak (2006: 378) and suggested previously by, e.g., Jassem (1962) and Lindblom (1963). The lack of a phonological vowel length contrast certainly contributes to this characteristic.

Global and local linear measures of segmental variability known as ‘rhythm metrics’ have been used to classify languages according to the traditional rhythm taxonomy, with very limited success (for formal and empirical critique, see especially Cummins 2002; Gibbon 2006; Arvaniti 2012). Nonetheless, in a study by Ramus et al. (1999), a short text read by four Polish speakers exhibited high standard deviation of consonantal intervals (ΔC) and a low proportion of vocalic intervals (%V). Also, a very low value of the vocalic variability index (ΔV) was obtained. The combination of the above segment-based values placed Polish out of the parameter space delimited by the canonical stress-timed and syllable-timed types and motivated Ramus et al. (2006) to suggest devising a rhythmic ‘category of its own’ for the language.

Some recent studies indicate that the syllable might be the domain to look at when characterising the rhythm of Polish. Gibbon et al.’s (2007) study of a Polish corpus found nPVI values (a normalised pairwise variability index, i.e., a difference measure between adjacent intervals) for syllable duration to be lower than what had been typically found for Polish segmental intervals. The result suggested a greater regularity of syllabic intervals relative to segmental ones, despite large consonant clusters admitted in the phonology. Gibbon et al. (2007) proposed that the tendency towards syllable isochrony could be accounted for by (i) a Zipf effect: ‘large clusters are rare’, or (ii) compensatory effects operating within the syllable domain, or (iii) the lack of vocalic quantity contrasts and the general
'inflexibility' of Polish vowels, both contributing to consonant-vowel ratios within syllables that are closer to 1. A tendency for uniform durations of syllables in corpus studies was also found using different methods by Wagner (2007) and Malisz (2011). The above results highlight the contradictory patterns postulated in previous qualitative, phonological studies of rhythm in Polish, and it is difficult at this stage to determine its exact nature.

The rhythmic type and the status of associated phonological and phonetic features is less controversial for German. German has been classified as stress-timed (Kohler 1982), similar to most Germanic languages. Function words have weak forms with increasing levels of vowel reduction depending on speech rate and speech style. Many other phonetic reductions and deletions in running speech have been attested in German. In Helgason and Kohler’s (1996) corpus study more than half of post-accented vowels underwent deletion. Deletions and reductions might serve as manifestations of compensatory shortening that preserve more or less equal duration of inter-stress intervals. Phonemic vowel length contrasts exist in German, further contributing to greater vocalic variability vis-à-vis Polish, which does not contrast vowel length. There are two vowels, [a] and [e], in German which occur in unstressed syllables only (Wiese 2000).

A tendency for foot isochrony in German was found by Kohler (1986) using nonsense stimuli with variable syllable count and structure. Domahs et al. (2008) found evidence that the hierarchical organization of syllables and feet plays a role in word stress processing in German. In contrast, no such evidence was found for Polish (Domahs et al. 2012).

2.2.2 Speech rate

Malisz (2013), in a dialogue corpus of 8 Polish participants (of which a subset of 6 participants is analysed here), found an average speech rate of 6.9 syllables/s (between speakers SD = 0.4). Dellwo and Wagner (2003) demonstrated that a simple syllable rate metric is able to distinguish between purported rhythmic groups by independently manipulating speech rate and comparing the self-reported ‘normal’ rates for languages from different rhythm classes. The mean value for speech tempo in Polish found in Malisz (2013) corresponds to what was reported to be the normal speaking rate for French subjects (normal range between approx. 6.3 and 7.2, mean = 7.3 syllables/s) in Dellwo and Wagner (2003). Dellwo and Wagner explain that cross-linguistic differences in the normal speaking rates observed in their study (with English at mean 5.9 and German at 5.6) might depend on the complexity of phonotactic structure. German is slower than Polish; even though both languages possess complex onsets and codas, the pres-
ence of vocalic quantity contrasts and heavy reliance of prominence on duration in German might contribute to the lower frequency of German syllables per second. Polish behaves similarly to French in the speech rate dimension; however, some of the possible structural reasons for the ‘syllable-timing effect’ are different than in French or Spanish, as suggested in Section 2.2.1.

Vocalic and consonantal variability measures (cf. 2.2.1) place German in the stress-timed space; however, the values tend to vary as a function of speech tempo (Dellwo 2006). Regardless of robustness issues attributed to ‘rhythm metrics’ and tempo variation, vocalic variability in German tends to approximate values found for syllable-timed languages with increasing speech rate, probably due to compressibility constraints on further segmental reduction. However, as Dellwo (2006) notes, higher speaking tempo also induces deletion of stress clashes and stressed syllables facilitating foot-timing.

2.2.3 Stress and prominence patterns

Primary lexical stress in Polish falls on the penultimate syllable with few exceptions and is thus predictable and presumably may serve as a marker of word boundary. The status of secondary stress is disputed from a phonetic perspective (Dogil 1999; Steffen-Batogowa 2000) but phonologically it is believed to fall on the first syllable (Kraska-Szlenk 2003). Polish listeners are sensitive to deviations from the default penultimate pattern as shown by Domahs et al. (2012) in an ERP study.

German shows a tendency for penultimate stress in morphologically simple words, though in more complex words, various rules determine the stress placement. Hall (1992: 23) states that German word stress is “probably one of the least understood and certainly one of the most controversial aspects of German phonology”. Along these lines, stress rules and their sensitivity to morphological and prosodic structure are a matter of debate (cf., e.g., Wurzel 1980; Giegerich 1985; Eisenberg 1991; Vennemann 1991). One possible account of German stress is based on the assumption that the prosodic foot is a domain of stress assignment, whereby several additional rules should be postulated in order to include the variety of different stress patterns in German (Wiese 2000; Domahs et al. 2008). On the other hand, according to Jessen (1999), German stress is not predictable and as such cannot predict word boundaries (cf. Cutler and Norris 1988).

Traditionally, Polish lexical stress has been described as acoustically primarily correlated with intensity (Dłuska 1950). However Jassem (1962), in an early acoustic study of Polish lexical stress, suggested that pitch movement is its most salient correlate. Similarly, Dogil (1999) showed that in the position of no focus,
primary stress in the target word is characterised by the highest $F_0$ with a sharp pitch slope. Under broad focus, “Polish word stress simply marks a position for the association with a pitch accent of the intonational structure” (Dogil 1999: 289). This means that lexical stress in Polish is in itself acoustically weak, context dependent, and functions as a potential for pitch accent, thus strongly interacting with the intonation structure of a sentence. Notably, in all the above studies, duration has no, or only weak, influence on stressed vowels, contrary to German which expresses word stress primarily by duration (before pitch and intensity changes [Jessen et al. 1995; Jessen 1999]).

Malisz and Wagner (2012), on the basis of a Polish dialogue corpus, studied three levels of perceptual prominence (no prominence, weak prominence, and strong prominence) and their relation to a number of acoustic features. Overall, non-prominent syllables were distinguished from all prominent ones by maximum pitch and mean intensity difference. Between weakly and strongly prominent syllables, duration was also a significant predictor. This suggests that acoustic correlates of prominence in Polish manifest themselves largely in phrase accentuation structure not in the lexical stress domain, as suggested by Dogil (1999). Overall intensity, duration, and pitch movement are good correlates of phrase accent. Lexical stress is weakly expressed acoustically, especially in the duration dimension, a clear difference from German. However, as supported by Domahs et al. (2012), prominence perception based on the expectation of lexical stress on the penultimate syllable is robust.

In general, prominence distinctions in German are mainly carried by duration (Kohler 1995); both lexically stressed and pitch accented syllables are considerably longer than unstressed ones. Sentence prominence in German is acoustically characterized by the following ranking of prosodic parameters: changes in fundamental frequency, duration, and intensity (Andreeva and Barry 2012).

3 Acoustic study

3.1 Experimental design

3.1.1 Material

Our interest lies in the ways word and phrase boundaries as well as prominence are realized in two languages that differ considerably in prosodic structure. Glottal marking can contribute to all of the above phenomena. Both glottal marking and rhythmic processes presumably function to structure the speech flow into higher units. We are additionally interested in how rhythm interacts with glottal marking in this function.
We analyse two different speech styles: spontaneous and ‘prepared’ speech. The material consisted of a spontaneous speech dataset comprising (a) Polish task-oriented dialogues (Karpiński et al. 2009) and (b) recordings of spontaneous dialogues in German (Buschmeier et al. 2011). We analysed word-initial vowels of four storytellers in the German corpus and six instruction-givers in the Polish corpus. In total, 401 tokens were analysed in German dialogues (ca. 20 min.) and 202 in Polish dialogues (ca. 30 min).

We also investigated samples of ‘prepared’ speeches2 given by four German and four Polish prominent speakers (ca. 40 min. recording time for each language). In total, 472 items in Polish and 885 items in German were analysed. The speakers selected for the analysis of German ‘prepared speech’ were Konrad Adenauer (1876–1967; first Federal German chancellor 1949–1963), Thomas Mann (1875–1955, famous writer and Nobel prize winner 1929), Richard von Weizsäcker (*1920, Federal German president 1984–1994), and Willy Brandt (1913–1992, chancellor of the Federal Republic of Germany 1969–1974). The acoustic analysis included three samples from speeches of each speaker:

a. Adenauer: 1929, 1949a, b (henceforth KA)
b. Mann: 1945, 1949, 1950 (henceforth TM)
c. von Weizsäcker: 1984, 1989, 1992 (henceforth RW)
d. Brandt: 1961, 1970, 1974 (henceforth WB)

For Polish, we analysed samples of the following prominent speakers: Jerzy Popiełuszko (1947–1984, priest associated with the “Solidarność” trade union), Władysław Anders (1892–1970, politician, army general), Władysław Sikorski (1881–1943, Prime Minister of the Polish government in exile 1939–1943) and Ryszard Kaczorowski (1919–2010, President of Poland in exile 1989–1990). The samples were excerpted from the following files:

a. Popiełuszko: 1984a, b (henceforth JP)
b. Anders: 1944, 1945, 1953 (henceforth WA)
c. Sikorski: 1940, 1941 (henceforth WS)
d. Kaczorowski: 1990 (henceforth RK)

The Polish recordings were obtained from Narodowe Archiwum Cyfrowe (National Digitalized Archive), and the German recordings were taken from the CD collection “Tondokumente zur deutschen Geschichte” (Audio documents of German history; Stiftung deutsches Rundfunkarchiv 2004ff.).

2 Selective results of three German and three Polish speakers are presented in Żygis and Pompino-Marschall (2012).
3.1.2 Annotation of glottalisation

The corpora were annotated in two main independent stages: ‘the glottalisation phenomena’ and ‘the prosodic domain’ stage. As suggested in the literature, different annotators were involved in the annotation processes. In total six annotators: two native speakers of German, three native speakers of Polish, and one native speaker of Egyptian Arabic annotated the data. All annotators were either phoneticians or have been trained in phonetics. The annotations were made in PRAAT (Boersma and Weenink 2009).

In the ‘glottalisation phenomena’ stage, word-initial vowels were identified and examined for the presence of (1) glottal stops, (2) glottalisation, and (3) vowels produced without any glottal marking. Importantly, the annotation of glottal marking type was based primarily on perceptual judgment and secondarily on the inspection of acoustic parameters following the procedure proposed in Dilley, Shattuck-Hufnagel, and Ostendorf (1996).

Acoustically, glottal stops are mainly characterized by a closure and the following burst, although the burst is not always fully manifest from inspection of the spectrogram. It is often accompanied by a lower $F_0$ and lowered amplitude (see also Hillenbrand and Houde 1996). Figure 1 provides an example of a glottal stop. Glottalisation is used as an umbrella term for irregularity in the acoustic waveform which, despite inducing similar perceptual impressions, can be manifested in different ways. It can be manifested as (1) highly irregular spacing

![Glottal stop at the initial position of aus 'from' as pronounced by speaker RW.](image-url)

Fig. 1: Glottal stop at the initial position of aus ‘from’ as pronounced by speaker RW.
of pitch periods (aperiodicity), (2) low $F_0$ accompanied by near-total damping of glottal pulses (or creak), (3) regular alternation in shape, duration, or amplitude of glottal periods (diplophonia), and (4) a momentary shift to a relatively high-pitched and low amplitude voice quality (glottal squeak) (see Redi and Shattuck-Hufnagel 2001). Figure 2 provides an example of glottalisation.

We did not base our analysis on acoustic measurements such as, e.g., $H1^*-H2^*$, i.e., a difference between amplitudes of the first two harmonics assumed to be a correlate of glottal opening (Holmberg et al. 1995) for two reasons: first, our analysis is primarily based on perceptual judgement, and secondly, $H1^*-H2^*$ is a controversial correlate of glottal opening (Kreiman et al. 2008). We are also aware that some tokens where the irregular vibration may have arisen from other articulatory manoeuvres than a sudden abduction or adduction of the vocal folds are also included in the analysis (see also Redi and Shattuck-Hufnagel [2001: 414] for a similar strategy). Again, perceptual judgements on boundary marking were decisive in those cases.

Generally, we observe that glottal stops and glottalisation create more salient cues perceptually in German than in Polish. Accordingly, their acoustic manifestation was much easier to detect in spectrograms and oscillograms of German data than of Polish data, a point which is reflected in the annotation procedure and in the number of annotators for a given language in particular, as described below.

![Fig. 2: Glottalisation at the initial position of aller ‘all’ Gen. Pl. as pronounced by speaker RW.](image-url)
Polish dialogues and speeches were independently annotated by two expert annotators (the first two authors of this manuscript). Inter-annotator agreement in two sampled Polish dialogues showed values of Cohen’s $\kappa = 0.5$ (moderate agreement, according to Landis and Koch 1977) or 70%, for three categories. In most cases labeling problems stemmed from the relative subtlety of the phenomena in Polish, as mentioned above, especially in spontaneous speech. Additionally, in the case of two dialogues, the audio quality was worse than in others and the dialogues had to be reviewed more carefully. In consequence, each case of disagreement was reviewed and discussed by both annotators until an agreement was reached. In addition, the data was (in part, especially with respect to uncertain cases) inspected by a native speaker of Egyptian Arabic. In Egyptian Arabic the glottal stop is part of the phonemic inventory. The cases flagged by the Arabic native speaker were reviewed again by both Polish annotators. A final decision was taken by the native experts. After this procedure the resolved cases were labeled on a separate tier and included in the analysis.

German dialogues and speeches were annotated by two phonetically trained experts: the second author of this manuscript annotated dialogues, and the third annotated speeches. However, at the beginning of the annotation processes, each file was annotated by both annotators. The decision to annotate the files separately was based on discussions of disagreement/problematic cases that were very few. In the remaining part of the annotation process, only the problematic cases were discussed. Therefore, no agreement was calculated. Finally, some problematic cases in dialogues were also discussed with a native speaker of Egyptian Arabic and a final decision was taken by the expert annotator.

### 3.1.3 Prosodic annotation and methods

Rhythmic prominences and phrasal structure were annotated using the Rhythm and Pitch system (Breen et al. 2010). The advantage of this system over, e.g., ToBI is that RaP is less dependent on language-specific phonological parameters of intonation and more on native perceptual judgments of acoustic parameters. Additionally, no ToBI system for Polish exists so far. Hence, in our case, RaP allowed for a more straightforward and compatible comparison of glottal marking between the two languages in the context of their different prosodic structure.

The annotation was conducted semi-manually: first, vowel onsets were marked by a Praat script (the ‘beat extractor’ by Barbosa 2006) and then corrected manually by two experts. The resulting intervals from one vowel onset to the other correspond to ‘phonetic syllables’. Subsequently, two native experts trained in RaP identified all rhythmically prominent phonetic syllables in terms
of two prominence levels: prominent and non-prominent. The annotation was based on perceptual judgments of the signal, i.e., a prominent syllable was marked when a ‘beat’ on a given syllable was actually perceived and not when phonological rules dictated lexical or sentence stress placement. Finally, the two experts checked each other’s annotation for obvious errors. No inter-rater reliability measures were calculated at this stage.

Minor phrasal boundaries were also delimited in all datasets. The RaP minor phrase boundary is defined as a minimally perceptible disjuncture. It approximately corresponds to the ToBI break index ‘3’ (Breen et al. 2010). All word-initial vowels received a label in a separate variable, ‘phrase position’, depending on whether they appeared in the middle or at the beginning of a minor phrase.

In order to characterise rhythmic structure variability, a method based on coupled oscillators as described in O’Dell and Nieminen (2009) was used (cf. Barbosa 2002). Coupled oscillator models of speech rhythm (Barbosa 2006, 2007; O’Dell and Nieminen 2009) usually utilise at least two universal oscillators, the syllabic oscillator and the phrase stress oscillator, that operate at distinct timescales (cf. Cummins and Port 1998; Tilsen 2009). The ‘task’ of the syllabic oscillator is to keep pace with the vowel onset sequence. Vowel onset sequences specify ‘phonetic syllables’. The phrase stress oscillator specifies both prosodic phrasing and prominence. Abstractly, the syllabic oscillator provides periodicity and interacts with (is coupled to) the phrase stress oscillator that provides structure (Barbosa 2006). The interaction between the tendency to preserve the periodicity of the syllabic cycle and the phrase stress cycle can vary. Duration patterns observed in speech data depend on the strength of coupling exerted by one oscillator on the other. This means that a model such as the one by O’Dell and Nieminen (2009) can express degrees of stress- and syllable-timing that often coexist in languages depending on, e.g., speech style as well as differences between languages themselves. The method is also able to express hierarchical relationships between relevant rhythmical units, unlike most linear ‘rhythm metrics’, mentioned in Section 2.2.1 (cf. Asu and Nolan 2006).

In our study, the syllabic oscillator is expressed by ‘phonetic syllables’, i.e., intervals between two consecutive vowel onsets. The phrase stress oscillator is expressed by Rhythmic Prominence Intervals. Rhythmic Prominence Intervals (henceforth RPI) were extracted from the RaP annotations, that is, by recording durations between one phonetic syllable marked as prominent and the next. The

3 A subset of the present material (Polish dialogues) contains prominence annotation on three levels: non-prominent, weakly prominent, and strongly prominent, the latter two were collapsed for the present analysis into one category: ‘prominent’, for uniformity with the remaining datasets.
intervals were extracted only from within fluent stretches of speech, excluding pauses. Additionally, prominences marked on phrase-final syllables were excluded from the analysis to avoid boundary lengthening phenomena interfering with the main utterance rhythm.

The relative coupling strength parameter $r$ expresses the interaction between the two coupled oscillators (O’Dell and Nieminen 2009). Relative coupling strength between the stress and syllabic oscillator was estimated empirically by:

a. measuring the durations of Rhythmic Prominence Intervals
b. counting the number of phonetic syllables comprising the RPIs
c. estimating intercept and slope coefficients by means of linear regression with the number of syllables as predictors of RPI duration
d. calculating the relative coupling strength as the ratio: $r = a/b$, where $a$ is the intercept and $b$ is the slope coefficient (Eriksson 1991; O’Dell and Nieminen 2009)

Separate regression models and $r$ values were calculated for each speaker and for both speech styles in Polish and German. In the prepared speech material, several speeches were given by some of the speakers on different occasions. Relative coupling strength values were determined for each of these speeches independently as well (see Appendix A).

The $r$ parameter is interpreted as follows: for values increasing over 1 the RPI oscillator exerts relatively more pressure on the syllable oscillator, i.e., there is a tendency for the RPIs to equalise their periods and hence the syllable duration has to adapt. For values decreasing below 1, the syllable period is relatively more ‘influential’, i.e., the coupling is determined by the syllable oscillator. In this case, RPI duration variability depends more on the syllable count within an RPI; it increases vis-à-vis syllable count more cumulatively. Since relative coupling strength is a ratio, the value of 1 is not a strict cut-off but indicates a situation where a language or style is neither ‘syllable’- nor ‘stress’-timed. The slope is dependent on speech rate; the higher the slope the slower the tempo.

We hypothesise for the purposes of the rhythmic structure sub-study that Polish will show a stronger tendency towards syllable oscillator dominance with possible weak phrase stress oscillator dominance in the ‘prepared speech’ material, given the following characteristics discussed in Section 2.2: (i) weak effect of lexical stress and a significant effect of pitch accent on duration with (ii) a structural (or merely statistical) tendency for uniform syllable durations. German should exhibit stable stress-timing with variation in the speech style dimension limited to coupling strength values over 1. Similar to Polish, a more pronounced dominance of the phrase stress oscillator in speeches, compared to dialogues, should be observed.
At the prosodic annotation stage we also calculated speech rate in syllables per second. We divided the number of syllables by the duration of the minor phrase. Minor phrase duration included anacrases and final syllables that were excluded in RPI extraction. Speech rate values corresponding to particular phrases in which word-initial vowels occurred were saved as the continuous variable ‘speech rate’.

### 3.1.4 Other annotations

Additionally, a difference between function and lexical words was marked. Also, the quality of the segment immediately preceding the initial vowel (vowel vs. consonant) and the quality of the word-initial vowel (low vs. mid vs. high) was recorded. These features were selected as controls, as they have been known to influence glottalisation phenomena (Krech 1968; Umeda 1978; Rodgers 1999).

### 3.1.5 Statistics

Statistical analyses were conducted in the R environment (R Development Core Team 2010). We used a logistic mixed model with a binomial dependent variable (glottally marked vs. unmarked) and subject as the random variable. The ‘glottal marking’ dependent variable included both glottal stops and glottalisation. We analysed the effect of the following parameters on ‘glottal marking’: (1) rhythm structure variability (the relative coupling strength predictor), (2) discourse, (3) speech rate, (4) prominence (prominent vs. non-prominent syllable), (5) phrase position (phrase initial vs. phrase medial), (6) word type (lexical vs. function words), (7) vowel height (low vs. mid vs. high vowels), and (8) preceding segment (vowel vs. consonant) for each language separately as well as several interactions as listed in the initial models in Appendix B. Speech rate data were log-transformed because of skewness in the distribution.

Finally, we also made use of a multinomial regression analysis in which the ‘glottal marking’ included three sublevels: ‘no marking’, ‘glottal stop’, and ‘glottalisation’, in order to consider the two types of glottal marking separately. Statistical results for both analyses in the present study are presented in detail in Appendix B. Since all logistic regression models used contain higher order terms such as interactions, all predictors were centered to reduce multicollinearity (Jaeger 2008).
4 Results

4.1 Rhythmic structure

We first examine the results of the rhythmic structure analysis. Appendix A presents the relative coupling strength values \( r \) for all styles, speakers (8 speakers of German and 10 speakers of Polish), and individual speeches in both languages \((N = 30)\). The values were estimated from separate simple linear regression models as described in Section 3.1.3. The coupling strength values per each individual speech or dialogue thereafter serve as an input predictor, ‘rhythm structure variability’, to logistic models for glottal marking.

The hypotheses sketched in Section 3.1.3 are largely borne out. The Rhythmic Prominence Interval cycle (the stress oscillator) dominates in German speeches \((r = 1.6)\). Polish speeches are also ‘stress-timed’ \((r = 1.65)\). In dialogues, Polish rhythmic structure is syllable-timed \((r = .8)\), whereas German stays within a stress-timed range \((r = 1.22)\).

There is a considerable overlap between \( r \) values for speakers in the prepared speech and the dialogue conditions in German \((p = .44 \text{ by Kolmogorov-Smirnov test})\). The difference between Polish dialogues and speeches is significant \((p < .01)\). It is also clear that Polish speakers in general can produce speech with values on both sides of the stress oscillator and syllable oscillator dominance (as well as those very close to 1). In this dataset, the tendency is for spontaneous dialogues to be either syllable-timed or ‘indeterminate’ and for speeches to be tendentially stress-timed. German speakers stay mostly at values well over 1 in both discourse conditions, i.e., in the stress cycle domain with even greater stress-timing in speeches. However, as indicated, the difference between the styles is not significant in German.

Speech rate, which systematically participates in the rhythmic structure measure adopted here, is difficult to study independently from coupling strength. However, since correlations between coupling strength and (log)speech rate were low (for German: Pearson’s \( r = -0.03 \), \( p = .2 \), for Polish: Pearson’s \( r = -0.09 \), \( p < .01 \)) and possible collinearity effects were further alleviated by continuous variable centering (see Section 3.1.5), both predictors were retained in the models. Overall speech rate in German (3.9 syllables/s) was slower than in Polish (5.1 syllables/s), as expected (cf. Section 2.2.2), with opposite trends between speech styles (Polish speech: 4.9 syllables/s vs. dialogue: 5.8 syllables/s; German speech: 4.2 syllables/s vs. dialogue: 3.2 syllables/s).
4.2 Patterns of glottal marking

We first look at each factor separately in order to point to the basic descriptive differences in influences on glottal marking between the two languages.

Our results show that glottal marking occurs significantly more often in German (63.4%) than in Polish (45%; $p < .001$, $\chi^2$ test), as shown in Figure 3. In both languages, vowel-initial words are produced more often with glottalisation than with a glottal stop (Polish glottal stop: 14% vs. glottalisation: 31%; German glottal stop: 23% vs. glottalisation: 40.4%). This result is presented in Figure 4.

Glottal marking appears to be discourse dependent in German: glottally marked words are produced less frequently in speeches (59%) than in dialogues (72.5%). In the same vein, in Polish words are less frequently glottally marked in speeches (41.5%) than in dialogues (53.5%). Figures 5 and 6 show the relative frequencies of glottal marking and glottal marking types depending on discourse in both languages. Moreover, the glottal stop is produced more often in German prepared speeches than in dialogues (German speeches: 28.7% vs. dialogues: 10.2%). Glottalisation, on the other hand, is used more frequently in spontaneous speech (German dialogues: 62.3% vs. speeches: 30.5%). In Polish, the glottal stop was slightly more prevalent in speeches (Polish speeches: 15.2% vs. dialogues: 10.9%), while glottalisation was more frequent in dialogues (Polish dialogues: 42.6% vs. speeches: 26.3%).

Our results also show that Polish and German differ with respect to the marking of prominent vowels. Whereas in both languages (and both styles), the majority of prominent vowels are glottally marked more often than non-prominent vowels (German: 84.7%; Polish: 58.1%), in German non-prominent syllables are also often glottally marked: ca. 51.7% of all non-prominent word-initial syllables are glottally marked, while in Polish 40.4% are pronounced with a glottal stop and/or glottalisation. Figure 7 presents the respective frequencies.

Another difference pertains to the glottal marking of phrase position. In Polish, phrase-initial position is more often marked (55.1%) than phrase-medial position (34.6%). In German the differences in marking between phrase position are negligible: vowels marked phrase initially amount to 60.6% while those marked medially amount to 65.6%. The results are presented in Figure 8.

Next, it is apparent that in both languages glottal marking is strongly dependent on the very nature (i.e., tongue height) of the marked vowel itself, as seen in Figure 9. Low vowels are more frequently glottalised than non-low vowels (Polish: 74% of all low vowels, 46.8% mid, 31.7% high; German: 82% of all low, 59% mid, 50.5% high). Furthermore, in Polish 44.8% of vowel-initial words were glottally marked when the words were preceded by a vowel and 45.5% when they were preceded by a consonant. Similarly, in German 64.7% of vowel-initial words were
Fig. 3: Relative frequencies of glottally marked and unmarked word-initial vowels for Polish and German.

Fig. 4: Relative frequencies of glottal stops, glottalisation, and unmarked word-initial vowels in Polish and German.
Fig. 5: Relative frequencies of glottally marked and unmarked word-initial vowels for two speech styles in Polish and German.

Fig. 6: Relative frequencies of glottal stops, glottalisations, and unmarked word-initial vowels for two speech styles in German and Polish.
Fig. 7: Relative frequencies of glottally marked and unmarked word-initial vowels for prominent and non-prominent syllables in German and Polish.

Fig. 8: Relative frequencies of glottally marked and unmarked word-initial vowels for initial and medial phrase positions in German and Polish.
Fig. 9: Relative frequencies of glottally marked and unmarked word-initial vowels for three vowel heights in German and Polish.

Fig. 10: Relative frequencies of glottally marked and unmarked word-initial vowels for lexical and function words in German and Polish.
glottally marked when preceded by a vowel and 62.4% when preceded by a con-
sonant.

Word type (lexical vs. function words) influenced the occurrence of glottal marking in Polish where more function words were glottalised: 50% of all function words and 37.7% of lexical words were glottally marked. In German an opposite scenario was found: while 77.3% of all lexical words were glottally marked, only 57% of all function words underwent glottal marking. The proportions are shown in Figure 10.

Next, we present the results of a generalised mixed model with a binomial dependent variable (glottally marked vs. unmarked and subject as the random variable) as well as multinomial regression, where in both analyses the influence of all effects, including the continuous log-transformed speech rate and relative coupling strength, were jointly analysed. Figure 11 for German and Figure 12 for Polish display only those effects that significantly contributed to the variance in final regression models. The ranking in terms of effect size is also shown. In addition, confidence intervals are given in brackets. In Appendix B detailed results are provided for the binomial mixed models and the multinomial regression models for both languages.

A generalised mixed model with a binomial dependent variable (glottally marked vs. unmarked) shows that the type of discourse significantly interacts with other factors. In German, the interaction of discourse type and speech rate predicts the occurrence of glottal marking. Glottal marking is 9.02 times more likely ($p < .001$) to occur in German dialogue with increasing speech rate. More specifically, as the multinomial analysis reveals, glottal stops are found more frequently in speeches ($p < .001$) and glottalisation more frequently in dialogues ($p < .001$).

However, the main effect of speech rate on glottal marking is negative overall ($p < .001$), i.e., as speech rate increases, glottal marking is less probable. Multinomial analysis reveals that the result is mainly based on the behaviour of glottal stops: as speech rate increases, the frequency of glottal stops decreases ($p < .001$).

In Polish, the interaction of discourse type and rhythm significantly influences glottal marking: as the value of $r$ increases, the probability of a glottally marked word-initial vowel increases 5.89 times ($p < .02$) in dialogues. Note that Polish dialogues ranged from $r = .3$ (strongly syllable-timed) to $r = 1.25$ (‘indeterminate’ to stress-timed, cf. Section 4.1). This result also means that in speeches, as $r$ decreases, the probability of glottal marking increases. Note that Polish speeches ranged from $r = 0.85$ (syllable-timed) to $r = 2.8$ (strongly stress-timed). Multinomial regression confirms this result ($p < .01$ for glottalisation; $p < .05$ for glottal stops) and also shows that glottalisation is more frequently found in dialogues than in speeches ($p < .01$).
**Fig. 11:** Effect sizes and 95% confidence intervals from binomial regression analysis for German.

**Fig. 12:** Effect sizes and 95% confidence intervals from binomial regression analysis for Polish.
Next, glottal marking in German is strongly prominence dependent. The glottal stop and glottalisation phenomena are 3.73 times \( (p < .001) \) more likely to occur in a prominent syllable than in a non-prominent one. In Polish, on the other hand, prominence has less predictive power: prominent syllables are 1.62 times more likely to be glottally marked than non-prominent ones \( (p < .02) \). In both languages both types of glottal marking are predicted to increase in a prominent position (German: \( p < .001 \) for glottalisation and \( p < .001 \) for glottal stops; Polish: \( p < .01 \) for glottalisation and \( p < .01 \) for glottal stops).

The effect of prominence in German also significantly interacts with phrase position \( (p < .02) \): Non-prominent vowels in phrase-medial position are less likely to be marked than non-prominent vowels in initial position. Importantly, prominent vowels in general are more likely to be marked but less so in initial position. Because of these opposing phrase position effects depending on the level of prominence, the main effect of initial phrase position in German does not survive (cf. Figure 8).

Multinomial analysis of German data, however, suggests a complementary distribution of the two analysed types of glottal marking relative to their position in a phrase. Glottal stops are predicted to appear more often in the phrase-initial rather than phrase-medial position \( (p < .001) \) while glottalisation is more likely to appear in the phrase-medial than in the phrase-initial position \( (p < .01) \).

In Polish, we again find a significant interaction between position and prominence \( (p < .02) \) exhibiting the same pattern as in German. But contrary to German, the effect of initial phrase position in general is great enough to have an overall positive effect on glottal marking probability \( \text{odds ratio 1.93, } p < .001 \), regardless if a vowel is prominent or not. Additionally, multinomial analysis shows that glottalisations appear less often in the phrase-initial than phrase-medial position \( (p < .01) \).

The results also indicate other significant interactions for phrase position in Polish: phrase position and word type interact in that lexical words in phrase-initial position are more likely to be glottally marked than in medial position \( \text{odds ratio 2.49, } p < .02 \). This result applies to both glottalisation \( (p < .05) \) and glottal stops \( (p < .01) \). However, word type alone is not a significant predictor of glottal marking in either Polish or German.

Furthermore, the main effect of vowel height is highly significant for both languages \( (p < .001) \) and all types of glottal marking (as shown by both binomial and multinomial regression analyses). Low vowels are more frequently glottalised than high ones in both languages \( \text{odds ratio for German 1.78; odds ratio for Polish 2.32} \). Moreover, vowel height and phrase position enter a significant interaction, i.e., the low vowel is more likely to be marked in the initial position (Ger-
man: $p < .01$; Polish: $p < .05$). Finally, the main effect of preceding segment is insignificant in both languages.

5 Discussion and summary

Our results show that German and Polish significantly differ from each other not only with respect to the frequency of glottal marking (higher in German than in Polish) but also with respect to the parameters that determine it.

In the present study we dealt with very different datasets. The datasets varied not only between languages, styles, and speakers, but also diachronically. However, we were able to show that first of all, the physiologically determined effect of word-initial vowel height is consistently present across the datasets and also explains a lot of the variance. Low vowels are always more often glottalised than non-low ones, cf. a similar result by Krech (1968). This is closely linked to the articulatory settings of low vowels which are more favourable for glottalisation than the articulatory gestures of high vowels (cf. Żygis, Brunner, and Moisik 2012).

A complex picture emerges in Polish dialogues. The specific dataset contained a lot of phrase-initial function words, especially conjunctions such as *i* ‘and’ or *a* ‘and/but’. In the type of task-oriented dialogue, the speaker gives instructions to the dialogue partner that typically form a number of steps to be made to ensure the task’s success. Instructions often start with expressions such as “and now take the sheet of paper/do this/turn the sheet around”, etc., following a pause. Consequently, we initially found higher proportions of glottalised function words in Polish (see Figure 10). Regression models, however, show that lexical words in initial position receive more glottal marking than function words in initial position. Since function words often create prosodic words with the following lexical words (Kraska-Szlenk 2003), glottal marking of function words can be also partly interpreted as a marking of a prosodic word boundary. In German, as our results show, word type does not predict glottal marking.

Prominence, as indicated previously by others (e.g., Dilley, Shattuck-Hufnagel, and Ostendorf 1996), can be expressed by a glottalisation index, among other cues. This is the case especially in German but also in Polish. We predict that an increasing level of prominence will correlate with a more salient glottal marking. The much stronger effect of prominence on glottal marking in German compared to Polish contributed to the observed perceptual salience of glottal marking in German vs. Polish. The phenomena are much more subtle in auditory perception in Polish because they do not correlate with the assignment of prominence as strongly as in German. In addition, non-prominent vowels are marked fairly frequently in German (51.7%).
Phrase effects depend on a number of factors and vary across languages. No main effect of phrase position was found for German. If we look at glottal stops and glottalisation separately, it appears that in German more glottal stops are found phrase initially than phrase internally, and the opposite applies to glottalisation, which appears phrase internally more often than phrase initially. The differences are, in our opinion, not linked to different functions of glottal stops and glottalisation, but to different contexts conditioning the presence of glottal marking. Glottal stops require more precise articulation conditions that are more optimal in the phrase-initial position, especially after a pause (see, e.g., Rodgers 1999).

In Polish, glottal marking is found more frequently phrase initially than phrase internally. Glottal marking of the phrasal domain is also ranked higher than prominence in terms of effect size in Polish. Beckman (1992) suggested that stress-timed languages prefer prominence (head) marking over prosodic domain (edge) marking, whereas syllable-timed languages signal both prosodic functions. In our results, German strongly utilises glottal marking as a prominence cue. Polish employs glottal marking significantly in both functions: as a signal both strengthening the phrasal domain and enhancing prominence.

Along these lines, we propose that German, with stress timing, mobile lexical stress, and relatively more variable syllable durations than Polish, marks initial vowels more frequently. Polish, in turn, with relatively more even syllable durations and predictable penultimate stress, does not mark prominent syllables at the word-initial boundary as strongly and as often, but rather at phrase-initial boundaries. While words are particularly frequently glottally marked in German in order to facilitate rhythmic grouping, Polish uses glottal marking more sparingly, mainly to indicate phrase edges.

This leads us to the specific investigation of a rhythmic variability effect on glottal marking rate in the different stylistic contexts and languages. The rhythmic variable \( r \) approximates the relative coupling strength between the phonetic syllable and the Rhythmical Prominence Interval. These two intervals are nested, interacting rhythmic cycles that are assumed to express two coupled oscillators relevant for the rhythm of Polish and German. The variation in the coupling strength between these cycles approximates the complexity of rhythmic variation between languages and speech styles in a more complete fashion than, e.g., so-called ‘rhythm metrics’. In particular, our results indicate that Polish speakers straddle both sides of the continuum determined by coupling strength, while German speakers stay in the stress oscillator dominance territory. These results are in line with what has been known about the rhythmic structure of both languages. But more importantly, relative coupling strength provides a single parameter that quantifies the relevant rhythmic variability and can be used to explain other phenomena, such as glottal marking.
Our results suggest that glottal marking depends on the type of rhythmic structure of a given language or style. Our Polish data present a case where a variety of timing strategies reveal an effect on glottal marking that is apparently not evident in German, which instead exhibits rather uniform stress timing across styles. The difference in $r$ values between speech styles is significant in Polish. The distribution of $r$ values for Polish dialogues ranges from extremely syllable oscillator dominated ($r = 0.3$) to ‘indeterminate’ (values around 1) to somewhat stress-timed ($r = 1.25$). We find that in dialogues, as relative coupling strength values tend towards a stronger syllable oscillator influence, glottal marking increases in frequency. In speeches, the increase in coupling strength of the phrasal stress oscillator induces less frequent glottal marking. We propose that in dialogues perceptual predictability and grouping via the syllable cycle dominated rhythm (and predictable stress) is less available for coupling strength values around 1; hence, the increase in glottal marking is used as an enhancement. In speeches, as we move towards more reliable phrasal stress cycle dominance (from $r = 0.85$ up to $r = 2.8$), glottal marking as a ‘grouping enhancement tool’ is less needed and tends to decrease.

We found a dependence of glottal marking on correlates of rhythmic structure in German, e.g., discourse, prominence, and speech rate. From a theoretical point of view, it is possible that coupling strength variability expresses prosodic differences in speaking style: rhythmic prominence distribution, durational characteristics, and speech style. However, the variability along the coupling strength parameter in German was not large enough to show a potential rhythmic effect, and speech rate has a very strong effect on glottal marking in German. Faster rates reduce glottal marking in general and especially so in speeches where glottal stops are dominant. In dialogues, faster rates increase the occurrence of glottalisation phenomena. To what extent the effect of fast speech attenuates the physiological ability to produce glottal stop gestures and to what extent speech rate effects are in fact rhythmic effects will be left for further study.

In summary, it appears that the chameleon-like behaviour of glottal stop and glottalisation can be at least partly better understood if several different parameters including the rhythmic structure of a given language are taken into account. Future work will show the extent to which glottal marking aids the recognition of word boundaries if rhythmic parameters are manipulated, a point which has been already partially investigated in other languages such as Czech, English, Slovak, and Spanish (Bissiri et al. 2011; Volin et al. 2012; Heffner et al. to appear). We leave the issue open for further studies in German and Polish.
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## Appendix A

**Table A.1:** Relative coupling strength ($r$) values for German data.

| Language | $r$ | Discourse | $r$ | Subject | $r$ | Individual speeches | $r$ |
|----------|-----|-----------|-----|---------|-----|---------------------|-----|
| German   | 1.46| Speech    | 1.6 | KA      | 2.4 | Adenauer (1929)     | 2.36|
|          |     |           |     |         |     | Adenauer (1949a)    | 2.2 |
|          |     |           |     |         |     | Adenauer (1949b)    | 2.7 |
|          | RW  | 1.25      |     | Weizsäcker (1984) | 1.3 |
|          |     |           |     |         |     | Weizsäcker (1989)   | 1.4 |
|          |     |           |     |         |     | Weizsäcker (1992)   | 1.44|
| TM       | 1.07|           |     | Mann    | 2.4 | 1945                |     |
|          |     |           |     |         |     | Mann (1949)         | 1.68|
|          |     |           |     |         |     | Mann (1950)         | 1.2 |
| WB       | 1.82|           |     | Brandt  | 2.66| 1961                |     |
|          |     |           |     |         |     | Brandt (1970)       | 2.14|
|          |     |           |     |         |     | Brandt (1974)       | 1.74|
| Dialogue | 1.22|           | fem1| 1.66    |     |                     |     |
|          |     |           | fem2| 1.3     |     |                     |     |
|          |     |           | male1| 1.8    |     |                     |     |
|          |     |           | male2| 1.4    |     |                     |     |

**Table A.2:** Relative coupling strength ($r$) values for Polish data.

| Language | $r$ | Discourse | $r$ | Subject | $r$ | Individual speeches | $r$ |
|----------|-----|-----------|-----|---------|-----|---------------------|-----|
| Polish   | 1.1 | Speech    | 1.65| JP      | 1.47| Popiełuszko (1984a) | 1.4 |
|          |     |           |     |         |     | Popiełuszko (1984b) | 1.45|
|          | RK  | 1.33      |     | Kaczmarski (1990) | 1.33|
|          | WA  | 1.5       |     | Anders (1944) | 0.85 |
|          |     |           |     | Anders (1945) | 2   |
|          |     |           |     | Anders (1953) | 1.6 |
|          | WS  | 2.21      |     | Sikorski (1940) | 1.6 |
|          |     |           |     | Sikorski (1941) | 2.8 |
| Dialogue | 0.8 |           | fem1| 1.23    |     |                     |     |
|          |     |           | fem2| 1.25    |     |                     |     |
|          |     |           | fem3| 0.7     |     |                     |     |
|          |     |           | male1| 1     |     |                     |     |
|          |     |           | male2| 0.8    |     |                     |     |
|          |     |           | male3| 0.3    |     |                     |     |
Appendix B. Statistical results

1 Binomial regression analysis for German

Initial model: lmer (Glottal marking ~ discourse + r + (log)speech rate + phrasal position + vowel height + preceding segment + word type + prominence + discourse: (log)speech rate + discourse:r + (log)speech rate:r + prominence:word type + phrase position:vowel height + phrase position:word type + preceding segment:phrase position + vowel height:word type + prominence*phrase position + (1|subject), family = binomial(link = "logit"), data = data.de, reflevel = "0");

Final model: lmer (Glottal marking ~ discourse + (log)speech rate + phrase position + vowel height + prominence + discourse:(log)speech rate + phrase position:vowel height + phrase position:prominence + (1|subject), family = binomial(link = "logit"), data = data.de, reflevel = "0");

|                  | Estimate | Std. Error | z-value | Pr(>|z|)   | exp(coef) |
|------------------|----------|------------|---------|------------|-----------|
| Intercept        | 0.94253  | 0.1784     | 5.281   | 1.29e-07***| 2.57      |
| Discourse        | 0.19857  | 0.3447     | 0.576   | 0.5646     | 1.22      |
| (log)speech rate | −1.2274  | 0.2764     | −4.439  | 9.02e-06***| 0.29      |
| Phrase position  | 0.11436  | 0.14847    | 0.770   | 0.4411     | 1.12      |
| Vowel height     | 0.5751   | 0.07732    | 7.439   | 1.01e-13***| 1.78      |
| Prominence       | 1.316    | 0.15893    | 8.281   | < 2e-16 ***| 3.73      |
| Discourse: (log)speech rate | 2.19953 | 0.4373   | 5.029   | 4.93e-07***| 9.02      |
| Phrase position : Vowel height | 0.3767 | 0.1550 | 2.431 | 0.0151* | 1.46      |
| Phrase position : Prominence | −0.7376 | 0.318 | −2.319 | 0.0204* | 0.48      |

Random effects:
Resid. Variance: Var = 0.17 (subject), Std. Dev. = 0.42
Reference category: 0 = no glottal marking; 1 = glottal marking (glottalisation + glottal stop).
Other reference categories: Discourse: ref = speech, Prominence: ref = non-prominent, Phrase position: ref = medial, Word type: ref = function word, Vowel height: ref = high vowel;
All independent variables were centered (Jaeger 2008).
Predicted probability: C-index = 0.765, Dxy = 0.53

2 Binomial regression analysis for Polish

Initial model: lmer (Glottal marking ~ discourse + r + (log)speech rate + phrasal position + vowel height + preceding segment + word type + prominence + discourse: (log)speech rate + discourse:r + (log)speech rate*r +
prominence*word type + phrase position:vowel height + phrase position:word type + preceding segment:phrase position + vowel height:word type + prominence*phrase position + (1|subject), family = binomial(link = "logit"), data = data.pol, reflevel = "0");

**Final model:** lmer (Glottal marking ~ discourse + phrase position + vowel height + word type + r + prominence + prominence:phrase position + discourse:r + phrase position:word type + phrase position:vowel height + (1|subject), family = binomial (link = "logit"), data = data.pol, reflevel = "0");

|                | Estimate | Std. Error | z-value | Pr(>|z|) | exp(coef) |
|----------------|----------|------------|---------|---------|-----------|
| (Intercept)    | 0.1364   | 0.227      | 0.6     | 0.5483  | 1.15      |
| Discourse      | 0.9862   | 0.57       | 1.7     | 0.08    | 2.68      |
| Phrase position| 0.6556   | 0.1953     | 3.36    | 0.000792*** | 1.93     |
| Vowel height   | 0.8413   | 0.1251     | 6.72    | 1.7932890e-11*** | 2.32 |
| Word type      | -0.3446  | 0.1979     | -1.74   | 0.0817  | 0.70      |
| r              | 0.2347   | 0.2747     | 0.85    | 0.39296 | 1.26      |
| Prominence     | 0.4803   | 0.2028     | 2.37    | 0.0179* | 1.62      |
| Discourse: r   | 1.7737   | 0.7726     | 2.29    | 0.0216* | 5.89      |
| Phrase position: Prominence | -0.8976 | 0.3990 | -2.25 | 0.0244* | 0.41 |
| Phrase position: Word type | 0.9114 | 0.3875 | 2.35 | 0.0186* | 2.49 |
| Phrase position: Vowel height | 0.4980 | 0.2525 | 1.97 | 0.04858* | 1.65 

Random effects:
Resid. Variance: Var = 0.17 (subject), Std. Dev. = 0.42
Reference category: 0 = no glottal marking; 1 = glottal marking (glottalisations + glottal stop).
Other reference categories: Discourse: ref = speech, Prominence: ref = non-prominent, Phrase position: ref = medial, Word type: ref = function word, Vowel height: ref = high vowel;
All independent variables were centered (Jaeger 2008).
Predicted probability: C-index = 0.76, Dxy = 0.51

3 Multinomial regression analysis for German

**Initial model:** vglm (Glottal marking ~ discourse + r + (log)speech rate + word type + phrase position + vowel height + preceding segment + prominence + discourse: (log)speech rate + discourse:r + (log)speech rate:r + prominence:word type + phrase position: vowel height + phrase position: word type + preceding segment: phrase position + vowel height: word type + prominence*phrase position, family = multinomial(), data = data.de);

**Final model:** vglm(Glottal marking ~ discourse + r + (log)speech rate + phrase position + word type + vowel height + prominence + discourse:(log)speech rate
+ r:(log)speech rate + phrase position:word type, data = data.de, family = multinomial());

|                          | Estimate | Std. Error | z-value | Pr(>|z|) | exp(coef) |
|--------------------------|----------|------------|---------|----------|-----------|
| 1: (Intercept)           | 0.1292009| 0.083898   | 1.539973| 0.06178347| 1.1379187 |
| 2: (Intercept)           | −0.5100603| 0.103239   | −4.940572| 3.894686e-07***| 0.6004593 |
| 1: Discourse             | 1.0073235| 0.183543   | 5.488223| 2.029987e-08***| 2.7382624 |
| 2: Discourse             | −0.7931719| 0.256670   | −3.090246| 0.0009999539***| 0.4524075 |
| 1: r                     | −0.0206729| 0.201199   | −0.102748| 0.4590815  | 0.9795393 |
| 2: r                     | −0.2631595| 0.205739   | −1.279091| 0.1004325  | 0.7686193 |
| 1: (log)speech rate      | 0.0899201| 0.072084   | 1.247441| 0.1061179  | 1.0940869 |
| 2: (log)speech rate      | −0.3553640| 0.080632   | −4.407245| 5.234687e-06***| 0.7009182 |
| 1: Word type             | 0.1101075| 0.188979   | 0.582643| 0.2800668  | 1.1163981 |
| 2: Word type             | 0.2972678| 0.214762   | 1.384170| 0.0831532  | 1.3461757 |
| 1: Phrase position       | −0.4654333| 0.156181   | −2.980082| 0.001440856***| 0.6278630 |
| 2: Phrase position       | 0.8998852| 0.185306   | 4.856219| 5.982418e-07***| 2.4593207 |
| 1: Vowel height          | −0.4127772| 0.083317   | −4.954285| 3.629837e-07***| 0.6618097 |
| 2: Vowel height          | −0.7616166| 0.097725   | −7.793467| 3.219647e-15***| 0.4669110 |
| 1: Prominence            | 1.2953687| 0.186469   | 6.946821| 1.868061e-12***| 3.6523425 |
| 2: Prominence            | 1.1729946| 0.214785   | 5.461249| 2.363982e-08***| 3.2316557 |
| 1: Discourse:            | −0.0030016| 0.125583   | −0.023902| 0.4904654  | 0.9970029 |
| (log)speech rate         | 0.6272013| 0.158257   | 3.963194| 3.697682e-05***| 1.8723630 |
| 1: r:(log)speech rate    | −0.4203026| 0.183428   | −2.291380| 0.01097072* | 0.6568480 |
| 2: r:(log)speech rate    | 0.0766038| 0.212656   | 0.360224| 0.3593398  | 1.0796143 |
| 1: Phrase position:      | −0.3642064| 0.347676   | −1.047544| 0.1474244  | 0.6947478 |
| Word type                |          |            |         |          |           |
| 2: Phrase position:      | −0.6619717| 0.380326   | −1.740536| 0.04088247*| 0.5158333 |

Reference category: 0 = no glottal marking; 1 = glottalisation, 2 = glottal stop
Other reference categories: Discourse: ref = speech, Prominence: ref = non-prominent, Phrase position: ref = medial, Word type: ref = function word, Vowel height: ref = low vowel;
All independent variables were centered (Jaeger 2008).

4. Multinomial regression analysis for Polish

**Initial model:** vglm (Glottal marking ~ discourse + r + (log)speech rate + word type + phrase position + vowel height + preceding segment + prominence + discourse:(log)speech rate + discourse:r + (log)speech rate:r + phrase position:word type + prominence:word type + phrase position:vowel height + preceding segment:phrase position + vowel height:word type + prominence:phrase position, family = multinomial(), data = data.pol);
Final model: vglm (Glottal marking ~ discourse + r + word type + phrase position + vowel height + preceding segment + prominence + discourse:r + word type:phrase position + phrase position:vowel height + phrase position:prominence, family = multinomial(), data = data.pol);

|                      | Estimate  | Std. Error | z value | Pr(>|z|)   | exp(coef)       |
|----------------------|-----------|------------|---------|------------|----------------|
| 1: (Intercept)       | −0.352969 | 0.148250   | −2.38095| 0.03371479*| 0.7025991      |
| 2: (Intercept)       | −1.033697 | 0.199010   | −5.19423| 0.03556894 |                |
| 1: Discourse         | 1.094166  | 0.396950   | 2.75645 | 0.002921627**| 2.98686920    |
| 2: Discourse         | 0.434418  | 0.587860   | 0.73899 | 0.2299565  | 1.5440636      |
| 1: r                 | 0.503073  | 0.218640   | 2.30089 | 0.01069892**| 1.5637952      |
| 2: r                 | 0.012771  | 0.310050   | 0.04190 | 0.4835722  | 1.0128528      |
| 1: Word type         | −0.408279 | 0.223250   | −1.82880| 0.03371479*| 0.6647935      |
| 2: Word type         | −0.198734 | 0.273430   | −0.72683| 0.2336651  | 0.8197682      |
| 1: Phrase position   | 1.115564  | 0.225580   | 4.94537 | 3.799969e-07***| 3.0512901    |
| 2: Phrase position   | −0.149772 | 0.283440   | −0.52841| 0.2986074  | 0.8609039      |
| 1: Vowel height      | −0.917228 | 0.142370   | −6.44271| 5.87E-05***| 0.3996254      |
| 2: Vowel height      | −0.832371 | 0.174530   | −4.76931| 9.24E-03***| 0.4350166      |
| 1: Preceding segment | 0.104576  | 0.196140   | 0.53317 | 0.296958   | 1.1102395      |
| 2: Preceding segment | 0.457383  | 0.262400   | 1.74305 | 0.04066244*| 1.5799340      |
| 1: Prominence        | 0.566681  | 0.225110   | 2.51737 | 0.00591173**| 1.7624074      |
| 2: Prominence        | 0.681631  | 0.280750   | 2.42785 | 0.007594312**| 1.9770991     |
| 1: Discourse:r       | 1.346575  | 0.574850   | 2.34250 | 0.00957752**| 3.8442364      |
| 2: Discourse:r       | 1.787325  | 0.869010   | 2.05765 | 0.01985514*| 5.9734511      |
| 1: Word type:Phrase position | 0.872934 | 0.437950 | 1.99324 | 0.02311759*| 2.3939236      |
| 2: Word type:Phrase position | 1.275634 | 0.531830 | 2.39856 | 0.00822984**| 3.5809722      |
| 1: Phrase position: | −0.245023 | 0.287870   | −0.85115| 0.197343   | 0.7826867      |
| Vowel height         | −0.857290 | 0.350180   | −2.44817| 0.0071792**| 0.4243106      |
| 1: Phrase position:  | −1.266625 | 0.443450   | −2.85632| 0.0021429**| 0.2817809      |
| Prominence           | −0.158410 | 0.545980   | −0.29014| 0.3858546  | 0.8534998      |

Reference category: 0 = no glottal marking; 1 = glottalisation; 2 = glottal stop
Other reference categories: Discourse: ref = speech, Prominence: ref = non-prominent, Phrase position: ref = medial, Word type: ref = function word, Vowel height: ref = low vowel;
All independent variables were centered (Jaeger 2008).