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Research Paper

How Much Voicing in Voiced Geminates? The Laryngeal Voicing Profile of Polish Double Stops

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Geminates (such as the double /k/ in Polish *lekki* "light") form a group of consonants that are mainly characterized by longer durations than the corresponding singletons. Most of the research has concentrated on durational and spectral properties of geminates in contrast to singletons. Much less attention has been paid to the realization of the voicing contrast in geminates and whether it is differently implemented than in singletons. In the current study, we contribute to this research with the data from Polish stop geminates. To this end, a total of 49 native speakers of Polish produced all stop geminates and corresponding singletons in wordforms of the same phonological make-up. The measurements included closure duration, voicing ratio, duration, and mean intensity of the release burst. The results showed that the voicing ratio was 0.69, classifying Polish stop geminates as mildly devoiced. There was a significant speaker-dependent variability in that some speakers devoiced all geminates, while others either partially devoiced or never devoiced. The analysis of interactions between geminates and singletons revealed that geminates cancelled voicing cues observed in singletons such as longer durations and lower intensity of the release burst. We discuss the current results in terms of voicing implementation in Polish and in relation to other geminating languages.

Keywords: geminates; Polish; voicing; stops; speech production.

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1. Introduction

Geminates are a group of consonants that are characterized by longer constrictions than singletons and for this reason they are frequently referred to as long consonants (Hankamer *et al.*, 1989). For example, in Polish, geminates contrast with their corresponding singleton counterparts in pairs such as *lekki* "light" vs. *leki* "medicines" or *ranna* "wounded" (fem.) vs. *rana* "a wound". The term encompasses both "true" (monomorphemic) and "fake" (assimilated or concatenated) geminates (e.g., Oh, Redford, 2012). Most of the research on geminates in the world's languages (reviews in (Kawahara, 2015; Kubozono, 2017)) has concentrated on temporal properties of the singleton/geminate contrast itself (e.g., Amano, Hirata, 2010; Esposito, Di Benedetto, 1999; Hamzah *et al.*, 2016; Kingston *et al.*, 2009; Kotzor *et al.*, 2016; Tagliapietra, McQueen, 2010), as well as of the neighboring vowels (e.g., Idemaru, Guion, 2008; Kawahara, 2006; Kingston *et al.*, 2009; Lahiri, Hankamer, 1988; Local, Simpson, 1999; Ohala, 2007; Pickett *et al.*, 1999; Port *et al.*, 1987). Much less attention has been devoted to voicing in geminate consonants. Sustaining voicing in obstruents is an articulatory challenge since it necessitates sufficient transglottal air pressure drop. This challenge appears to be especially pronounced in the case of geminates since they have a much longer closure (Ohala, 1983), which may be the reason why cross-linguistically voiced geminates are less frequent than their voiceless counterparts (Hayes, Steriade, 2004) and are classified as marked (Al-Tamimi, Khattab, 2018; Blevins, 2004; Hayes, Steriade, 2004; Ohala, 1983; Westbury, Keating, 1986).

Because longer consonant closures are typically linked to voiceless (fortis) articulations (Catford, 1977; Jaeger, 1978), a phonetic question emerges of how and to what extent "already-long" geminates organize their voiced/voiceless contrast both durationally and spectrally. A number of studies have investigated this issue with different results. Butcher (2004) found that in Italian stops voiced and voiceless singletons differed significantly in duration and pressure, but geminates differed only in pressure. On the other hand, Al-Tamimi and Khattab (2018) reported that in Lebanese Arabic geminate duration was the most important correlate for distinguishing the four-way contrast between voicing and gemination. When investigating the amount of voicing in closure, defining it is as proportion of detectable low-energy periodic activity to the total closure duration, some languages tend to devoice geminates partially or even fully, e.g., Japanese (Fujimoto, Kataoka, 2016; Hirose, Ashby, 2007; Hussain, Shinohara, 2019; Kawahara, 2006), Tashlhiyt Berber (Ridouane, 2010), while other languages such as Buginese (Cohn *et al.*, 1999) or Egyptian Arabic (Kawahara, 2006) appear to maintain voicing throughout the geminate closure. Much evidence here comes from Japanese. For example, Kawahara (2006) reported that Japanese speakers devoiced 60 % to 70 % of geminate closures, which was in line with a later study by Hirose, Ashby (2007), who found 47 % of devoicing in the total closure duration in Japanese geminates. The most recent study by Hussain, Shinohara (2019) showed that devoicing of Japanese may be even more robust at the level of 75 % to 80 % of the closure. Another issue is whether geminates follow singletons in changes in closure duration as a function of the voicing contrast in that voiced consonants are typically shorter than their voiceless counterparts. This effect has been found for Tokyo Japanese (Homma, 1981; Idemaru, Guion, 2008; but see (Hussain, Shinohara, 2019)) and Lebanese Arabic (Al-Tamimi, Khattab, 2018). In the current study, we contribute to the debate on the voicing contrast in geminate obstruents by providing data from Polish, a language where fake geminates prevail but the true ones also occur.

In this study, we aim to realize the following research tasks: (1) compare the proportion of voicing in the closure between voiced geminates and voiced singletons, and (2) compare closure durations between voiced and voiceless geminates and see if they match differences in the closure durations between voiced and voiceless singletons.

2. The types and distribution of Polish geminates

Polish is regarded as a true geminating language which allows tautomorphemic lexical geminates, as in *lekki* "light" (adj. m.) vs *leki* "medicines". Generally, apart from plosives, also nasal, fricative, and even affricate consonants may form geminates in intervocalic and, less frequently, initial positions. Although most geminates in Polish belong to the "fake" category, and even in less obvious cases a diachronic analysis would almost always reveal either a phonological assimilation or morphological concatenation as gemination sources, a native speaker, save a handful of linguists, is not likely to identify *lekki* or *wanna* "bathtub" as derived forms and manifest this awareness in any phonetic modification of such double consonants. Therefore these geminates gravitate towards the "true" category, which is in fact more reliably represented by numerous foreign borrowings, thus confirming the strong geminating potential of the Polish language. This potential is also illustrated, for example, by the word *fontanna* "fountain", a Latin or Italian borrowing, which features no geminate in the source language.

It is easy to observe that the occurrence of a double consonant letter clearly indicates a geminate in Polish pronunciation. Even if the source language allows no long consonants, a double consonant letter in the original (and borrowed) spelling may trigger gemination, as in the English word *hobby*. This tendency, however, as observed by Porzuczek and Rojczyk (2014), has been attenuated in more recent borrowings, e.g., *mobbing*, which come from non-geminating languages, such as English or German.

The distribution of geminates in Polish follows certain universal tendencies (cf. Thurgood, 1993; Muller, 2001; Pająk, 2009). There are fewer sonorant than obstruent geminates, the intervocalic position is the most typical, and coronal geminates (including the nasal) outnumber representatives of the other places of articulation. Except for the coronal nasal, very frequently geminated in Polish, voiced geminates are otherwise rather rare so, in general, voiced obstruent geminates are far less frequent than their voiceless counterparts.

The more marked distributional characteristics (Maddieson, 1985; Ladefoged, Maddieson, 1996; Dmitrieva, 2009) comprise the existence of word-initial geminates, e.g., *ssak* "mammal", including affricates, a category highly marked in this position, e.g., *dżdżownica* /dʐ̻dʐ̻ɔvʲɲitsa/ "earthworm" (see (Rojczyk, Porzuczek, 2019a; 2022) for a detailed presentation of geminate types in Polish). Potential word-final geminates or consonant-adjacent ones (only possible in concatenated fake geminates) are normally degeminated (Rubach, Booij, 1990), as in the noun-to-adjective derivation *Sewilla*→*sewil+ski*. Even in such examples, though, degemination is not always obligatory, e.g., *bez+stronny* /-s+(s)tr-/ "im+partial" (Pająk, 2009), and the reduction may not occur at all or remain incomplete.

3. The phonetic realization of Polish geminates

Polish geminates are realized phonetically using a prolonged consonant constriction as the primary cue.

Interestingly, quite a large proportion of affricate geminates are also pronounced with one release, while either the occlusion or the fricative phase is lengthened (Thurgood, Demenko, 2003; Porzuczek, Rojczyk, 2021). The geminate/singleton duration ratio varies across studies and seems to depend on the consonant class, e.g., 1.7 for affricates (Thurgood, Demenko, 2003), 2.4 for stops and 2.1 for fricatives (Malisz, 2013), up to 2.88 for nasals (Rojczyk, Porzuczek, 2014).

Unlike other geminating languages, Polish allows rearticulation (also in undisputable true geminates in borrowings, e.g., *pizza*), which is more frequent in citation forms, formal speech, or at lower speech rates. Other potential rearticulation triggers may be linked to the etymology of a word and segmental context (Kozyra, 2008). Naturally, rearticulation rate also differs depending on the consonant type. Figure 1 shows single-articulated (left) and rearticulated (right) productions of the word *Budda* /ˈbudda/. Rearticulation is manifested in the release burst of the first consonant.

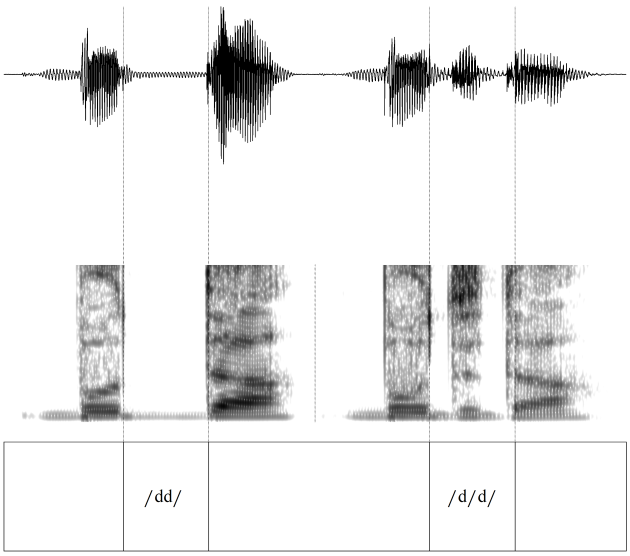

Fig. 1. Single-articulated (left) and rearticulated (right) productions of the word *Budda* /ˈbudda/ by the first author.

Rojczyk and Porzuczek (2019a) found that those with a more salient release phase (affricates and plosives) are rearticulated more often (35 % and 29 % of the cases, respectively), nasals, pronounced with an oral closure and unobstructed nasal air flow only in 18 %, while fricative geminates, as continuants, are hardly ever (2 %) separated by a vocalic insertion. It should be emphasized, however, that these mean figures must be perceived in the context of considerable cross-speaker variation, possibly reflecting the liquid boundary between natural/spontaneous and monitored speech. This boundary may also depend on particular experimental conditions or stimuli. For instance, in Rojczyk and Porzuczek's (2019a) experiment, devoted to a wider range of Polish geminates, the affricate rearticulation proportion (35 %) was much lower than in other studies focused particularly on affricates, which yielded a much larger rearticulation rate: 68 % in (Thurgood, Demenko, 2003) and 76 % in (Rojczyk, Porzuczek, 2019b). All these factors lead to various attitudes and reactions of the speakers, which is illustrated by the general results presented by Rojczyk and Porzuczek (2019a), where out of 48 native Polish participants, 16 produced only single-articulated geminates, while nine rearticulated more than 50 % of the tokens. It is possible that experimental conditions lead to hyperarticulation in a certain proportion of speakers but whether or not rearticulation is marginal in spontaneous speech is a question for a separate study regarding at least the speakers' sociolinguistic background and conversational contexts.

4. The phonological voicing contrast in Polish and its realization

As explained in the previous section, the realization and perception of geminates is strongly based on duration, which is also a parameter involved in cuing the phonological voicing contrast in the world's languages. This phonological contrast is naturally associated with the presence or absence of vocal fold vibration, but in fact, the presence or absence of vocal fold activity as the decisive voicing cue is only characteristic of true voicing languages, such as Catalan, Spanish or French (Solé, 2007), among others. Other languages (putting aside those with more complex phonation contrasts – cf. Cho *et al.*, 2019), the aspirating ones, such as, for instance, English and three varieties of German (Cho *et al.*, 2019), may also employ VOT variation, which results in phonologically significant timing adjustments. Polish, together with other Slavic languages, belongs to the former category of voicing languages, with negligible aspiration variation even in varying prominence positions (Malisz, Żygis, 2015).

The voicing contrast in obstruents is not always realized phonetically. Word-final obstruent neutralization is a characteristic feature of Polish, as well as numerous other languages. Some languages, e.g., English, also feature word-final devoicing, but they preserve the phonological contrast by the preceding vowel length modifications. The present study focuses on the intervocalic, post-stressed position, the most typical for geminates to occur in (Dmitrieva, 2017; and references therein). This position is rarely considered in the studies of voicing, and it is regarded as one where true voicing rather than VOT or vowel clipping is the main cue to the contrast. In Polish, the phonetic realization of word-internal intervocalic consonants reflects their phonological voicing category (as in *koza* /ˈkɔza/ "a goat" vs *kosa* /ˈkɔsa/ "a scythe"), although consonants in obstruent clusters tend to undergo either progressive (more typical of initial and final positions) or regressive assimilation, as in *łódka* /ˈwutka/ "a boat" or *prośba* /ˈprɔʑba/ "a request"[1]. The post-stressed intervocalic position generally preserves the voiced-voiceless distinction in obstruents (e.g., Lisker, 1957).

As mentioned in Introduction, voiceless consonants tend to be pronounced with longer constriction time, which is also true for a voicing language such as Polish. Rojczyk and Porzuczek (2019a) observed that voiceless plosive singletons were 30 % longer than their voiced counterparts. The difference amounted to 15 % in the case of geminates. The consonant length variation marking the two distinctions: voiced vs voiceless, and singleton vs geminate in Polish may interact with the characteristics of the glottal activity (vocal fold vibration) related to the constriction, and this interaction is examined in the present empirical study.

5. The current study

In the current study, we investigate the voicing profile of Polish stop geminates by addressing the following issues:

1) Are Polish phonologically voiced geminates devoiced and what is the magnitude of devoicing?
2) Is there observable speaker variability in the magnitude of devoicing?
3) Is the duration of voicing correlated with the duration of the closure?
4) Is there interaction of voicing and the geminate/singleton contrast for release duration and release intensity?
5) Are there atypical realizations of voicing in Polish stop geminates?

5.1. Materials

The materials included voiced and voiceless stop geminates for the three constriction positions in Polish – bilabial /bb/ vs /pp/, dental /dd/ vs /tt/, velar /gg/ vs /kk/ – and their corresponding singletons /b/ vs /p/, /d/ vs /t/, /g/ vs /k/. The targets were placed in an identical phonological context in potential Polish words represented orthographically as *Upe_ak* /uˈpɛ_ak/. The Polish orthographic system is transparent for stop consonants by cueing pronunciation in an unambiguous way. Accordingly, each consonant had the same word frame representation as shown in Table 1.

Table 1. Structure of the materials for recording.

	Geminate				Singleton			
	Voiced		Voiceless		Voiced		Voiceless	
Bilabial	bb	*Upebbak*	pp	*Upeppak*	b	*Upebak*	p	*Upepak*
Dental	dd	*Upeddak*	tt	*Upettak*	d	*Upedak*	t	*Upetak*
Velar	gg	*Upeggak*	kk	*Upekkak*	g	*Upegak*	k	*Upekak*

The choice for nonwords with this specific phonological structure was motivated by the desire to avoid the effects of unbalanced word frequency or familiarity with token pairs (Jurafsky *et al.*, 2001; Munson, Solomon, 2004; Raymond *et al.*, 2006), which may distort both durational and spectral relations between geminates and singletons. In other words, besides the desired word structure and measurement feasibility, we were looking for a context where the insertion of any plosive consonant should not form or closely resemble a real Polish word as the speakers may reduce or unnaturally boost the phonetic contrast in minimal pairs with varying lexical familiarity levels, even if associations are only based on word form similarity.

Moreover, previous research has shown that singleton/geminate contrasts are affected by the prosodic position within a word (Port, O'Dell, 1987; Amano, Hirata, 2010; Yoshida *et al.*, 2015). In order to reduce the impact of position and prominence level, the targets were placed in a carrier phrase *Pan Adam Upe_ak, panie prezesie* "Mr Adam Upe_ak, Mr. President". By using nonwords functioning as surnames, we provided plausible examples of acceptable Polish utterances with the tested item bearing phrase accent in a non-phrase-final position. Furthermore, it aided the speakers to sustain relatively stable tempo of articulation, which is especially important considering previous reports that overall tempo may influence geminate duration (Pind, 1995; Pickett *et al.*, 1999; Hirata, Whiton, 2005; Hermes *et al.*, 2021; Yoshida *et al.*, 2015; Ridouane, 2022). The target contrasts were interspersed with other contrasts (proportion 1 to 3) that served as distractors and were not used in the current study. They included the same word tokens with the singleton/geminate contrasts but with fricative and nasal consonants.

5.2. Participants

A total of 49 native speakers of Polish (39 females and 10 males) ranging in age from 19 to 22 (M = 20.08) participated in the study. They were all students at the University of Silesia in Katowice, Poland. All of them had pronunciation features of standard Polish without any dialectal traces. The unbalanced sample reflects the gender proportions in Polish students of humanities. Recruiting university students rather than ran-

[1] The realization of voicing in sandhi contexts, which are outside the scope of this paper, is more complex, and varies across regional dialects. For a phonological interpretation of the two main variants (see Cyran, 2011).

dom participants was to ensure more natural speech production and offset the effect of laboratory conditions, where the proportion of disfluencies even in short reading performance dramatically rises. None of the participants had spent more than two months outside Poland. Each speaker was paid 20 PLN (approximately 5 EUR) for their participation. None of the speakers reported any speech or hearing disorders.

5.3. Recording and measurements

All recordings took place in a sound-proof booth in the Speech Processing Laboratory, University of Silesia in Katowice. The speakers were seated in front of a 15-inch monitor screen which flashed the test phrases in black 28-point font against white background. The recording was self-paced in that the speakers read a phrase and proceeded to the next one by pressing an arrow key. The targets were randomized for each speaker individually. The signal was captured at 44 100 Hz through a dynamic Shure microphone fed by a Steinberg UR44 (Yamaha) audio interface unit stored as wav. files. Each session, which included other sound contrasts not used in the current study, took approximately 25 min, after which the speakers completed a questionnaire asking for basic personal data.

Measurements were taken from waveform and spectrograms using textgrids in Praat (Boersma, Weenink, 2001; n.d.). As discussed earlier, Polish has both single-articulated and rearticulated geminates. Only single-articulated productions were analysed in this study, because they have uninterrupted closure duration, compared to rearticulated geminates that have two release bursts. We decided to discard rearticulations (29 % in our recorded corpus) in order to obtain the results comparable to other languages which all have single-articulated geminates. Rearticulation was most frequently observed in velars (38.5 %), followed by dentals (37.2 %) and bilabials (24.4 %). Phonological voicing had a slight impact on rearticulation with 56.4 % of rearticulation in voiceless compared to 43.6 % in voiced geminates. Since the constriction duration is relevant for geminate/singleton contrast only in typical, single articulation, we have not decided to analyse the duration of the two constrictions in rearticulated geminates, where the additional release burst and/or vocalic epenthesis is a very clear indication of a doubled consonant. Moreover, the difference in articulatory complexity of the two variants made us refrain from direct comparison of respective temporal patterns. Moreover, the problem with rearticulated productions is that a large part the consonant duration is filled with the release burst of the second consonant. Frequently the closure durations are very short or even incomplete, which makes temporal durations of closure and periodic activity of voicing largely impossible. The example of rearticulation provided in Fig. 1 is an instance of careful clear speech by the first author for demonstrative purposes. In casual speech the closures (specially the first one) are either very short or even incomplete.

The following segmentation criteria were used (visualization in Fig. 2):

1) Closure phase was determined as a time interval between the offset of a preceding vowel indicated by a large drop in intensity and the cessation of formant structure (especially $F2$) and the onset of the following release burst indicated by a sudden rise of spectral energy.
2) Release phase was determined as an interval beginning with as the observable rise in (frequently aperiodic) energy to the onset of the following vowel marked by the emergence of visible formant structure.
3) Voicing in closure was determined as a period in the closure marked by low-frequency periodic energy (voice bar).

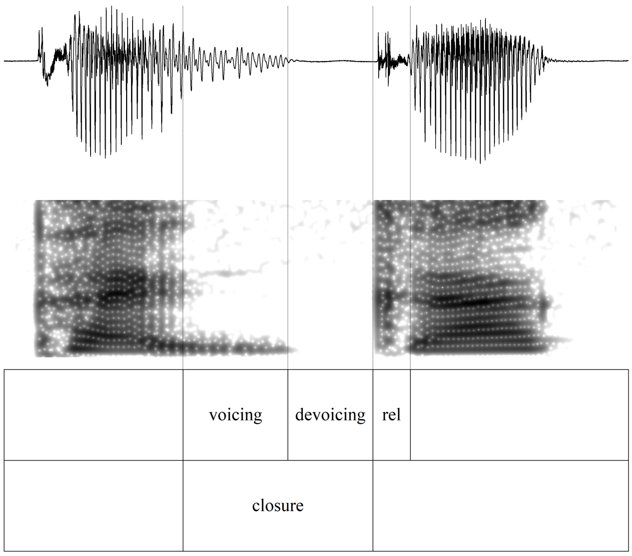

Fig. 2. Segmentation criteria based on the geminate /gg/ produced by Speaker 14 (female, age 20).

Each recorded token was inspected and measured manually by the authors. The following parameters were calculated: closure duration in milliseconds, voicing in closure in milliseconds, voicing/closure duration ratio (VC ratio: the proportion of voicing in closure to total duration of closure ranging from 0 to 1), release duration in milliseconds, and mean release intensity in dB. The release intensity was the mean intensity over the entire release burst. We found no cases of stop productions without a visible release burst. Although they may have differed in duration, there was always a visible plosion prior to the onset of the following vowel.

6. Analysis and results

Out of the recorded 588 targets (49 speakers × 6 geminates × 6 singletons) 41 (7 %) were discarded due to observable disfluencies, resulting in 547 valid tokens (267 geminates and 280 singletons). As mentioned earlier, rearticulated geminates were precluded from further analysis (78 cases, 29 %). The final corpus for acoustic measurements included 189 single-articulated geminates (92 voiced and 97 voiceless) and 280 singletons (137 voiced and 143 voiceless). We start our analysis by providing descriptive grouping analysis, which is followed by inferential statistics. We tested statistical significance of differences by using a mixed model analysis of variance in Statistica 13 (TIBCO Software Inc.) with speaker and word as random effects and the singleton/geminate contrast and the voiced/voiceless contrast as fixed effects. This is the model that utilises the method for estimating the variance of random factors which starts with constructing the sums of squares and cross product matrix for the independent variables. The sums of squares and cross products for the random effects are subsequently residualized on the fixed effects, leaving the random effects independent of the fixed effects. Between effects are tested for significance using relevant error terms based on the covariation of random sources of variation in the design using Satterthwaite's method of denominator synthesis (Searle *et al.*, 1992; Luke, 2017; TIBCO Software Inc., 2017). Finally, we provide individual atypical cases of voicing/devoicing in geminates together with their acoustic descriptions.

6.1. Voicing profile

The mean voicing ratio in voiced geminates was 0.69 (SE = 0.03). In order to quantify the proportions of voiced, partially devoiced and devoiced productions, we provided the following categorizations: 0.00–0.49 devoiced; 0.50–0.89 partially devoiced; 0.90–1.00 voiced (for different categorizations see (Davidson, 2016; Abramson, Whalen, 2017)). The analysis revealed that the distribution of the three categories was relatively equal with 33 % of voiced, 38 % of partially devoiced, and 29 % of devoiced productions. There was an observable between-speaker variability in the realization of voicing. Seven speakers (14 %) produced only fully voiced geminates, ten speakers (20 %) devoiced all geminates, and the remaining thirty-two speakers (66 %) produced partially devoiced geminates. The mean voicing ratio in voiced singletons was 0.91 (SE = 0.02). The majority of the productions (80 %) were fully voiced, 20 % were partially devoiced. No fully devoiced singletons were observed. The singletons had a significantly higher voicing ratio than the corresponding geminates [$F(1, 39) = 38.81$, $p < .001$, $\eta_p^2 = 0.5$)]. Table 2 presents means and standard error of the voicing ratio for each place of articulation.

Table 2. Means and standard error for the voicing ratio (ranging from 0 to 1) across the three places of articulation.

	Geminate		Singleton	
	M	SE	*M*	SE
Bilabial /b/	0.66	0.06	0.92	0.03
Dental /d/	0.75	0.05	0.96	0.01
Velar /g/	0.66	0.05	0.86	0.03

The prediction, based on aerodynamic principles governing sustaining voicing in closure, was that the shorter the duration of closure, the more voiced the consonant should be. Multiple regression analysis revealed that there was no significant regression between closure duration and the voicing ratio in geminates [$b^* = -0.17$, $R2 = 0.29$, $F(1, 90) = 2.64$, $p = 0.11$], however, as indicated by a negative b^* value, shorter closure durations tended to predict more voicing. The same regression for singletons yielded a significant result [$b^* = -0.18$, $R2 = 0.32$, $F(1, 134) = 4.32$, $p = 0.04$], revealing that in the case of geminates shorter closures predicted more voicing. Figure 3 shows the scatterplot regression lines for geminates (left) and singletons (right).

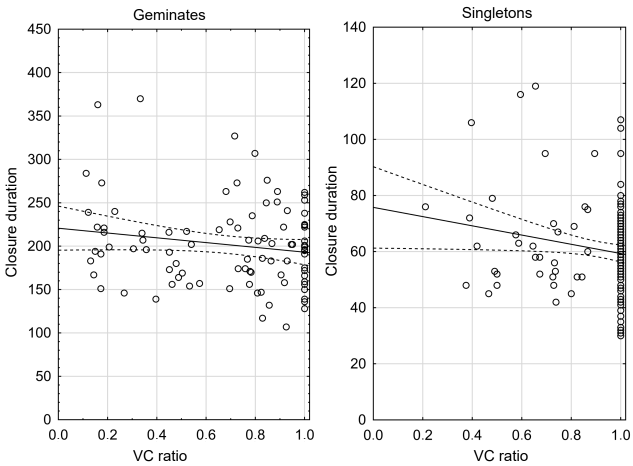

Fig. 3. Scatterplot of interaction between closure duration and voicing-to-closure ratio (VC ratio) in voiced geminates (left) and singletons (right).

Phonologically voiced geminates had a significantly shorter closure duration ($M = 202$, SE = 5.15) than their voiceless counterparts ($M = 239$, SE = 5.25) [$F(1, 37.7) = 30.63$, $p < 0.001$, $\eta_p^2 = 0.45$]. This difference was not accompanied by statistically significant differences in duration of the release burst between voiced ($M = 19.4$, SE = 0.88) and voiceless ($M = 21.4$; SE = 1.12) geminates [$F(1, 49.04) = 1.1$, $p = 0.3$]. Figure 4 shows mean closure and release duration for voiced and voiceless geminates and Table 3 presents numerical values across the three places of articulation.

Table 3. Means in millisecond and standard error for the closure duration and release duration in voiced and voiceless geminates across the three places of articulation.

	Voiced geminates				Voiceless geminates			
	Closure duration		Release duration		Closure duration		Release duration	
	M	SE	*M*	SE	*M*	SE	*M*	SE
Bilabial /b/	220.3	10.4	12.3	0.68	254.1	7.83	14.2	1.08
Dental /d/	205.6	8.78	16.9	0.85	235.6	10.92	18.6	1.22
Velar /g/	183.1	6.65	27.5	1.21	224.3	8.15	33.3	1.65

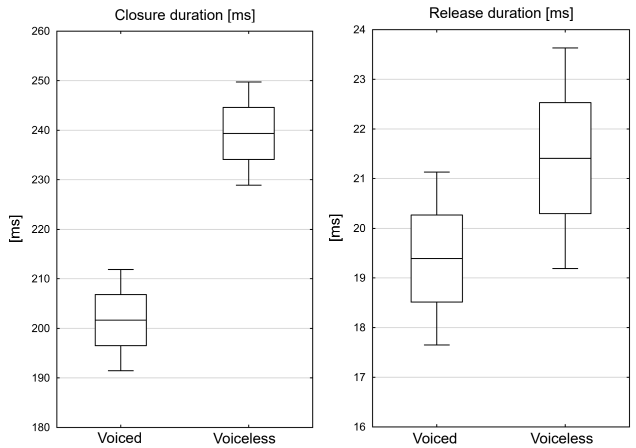

Fig. 4. Closure duration (left) and release duration (right) in ms in voiced and voiceless geminates. Lines = M, boxes = SE, whiskers = 0.95 CI.

6.2. Interaction of voicing and the geminate/singleton contrast

The recorded singletons had a mean closure duration of 61 ms (SE = 1.4) for voiced and 75 ms (SE = 1.38) for voiceless productions. The release burst had a mean duration of 16.1 ms (SE = 0.79) for voiced and 25.9 (SE = 1.05) for voiceless singletons, respectively. Statistical analyses of the observed differences showed that voiced singletons had a significantly shorter closure [$F(1, 46.57) = 53.16$, $p < 0.001$, $\eta_p^2 = 0.53$] and release burst [$F(1, 47.2) = 84.71$, $p < 0.001$, $\eta_p^2 = 0.64$]. Table 4 presents numerical values for closure and release duration in singletons across the three places of articulation.

The computations of the interaction between the closure duration, the voiced/voiceless contrast, and the singleton/geminate opposition yielded a significant result [$F(1, 34.05) = 11.04$, $p = 0.002$, $\eta_p^2 = 0.25$]. The analysis of the interaction (Fig. 5 top) shows that, even though post-hoc comparison revealed that voiced productions were significantly shorter for both singletons and geminates [Bonferroni, both $p < 0.001$], the effect of shortening was greater in magnitude for geminates. This effect clearly results from the fact that geminates have considerably longer closure durations and thus have more room for durational variability. The analysis of the release burst duration using the same interaction of the voiced/voiceless contrast and the singleton/geminate opposition (Fig. 5 middle) yielded another significant result [$F(1, 42.86) = 36.18$, $p < 0.001$, $\eta_p^2 = 0.46$). In this case, however, post-hoc Bonferroni tests revealed that duration of the release burst was significantly longer for voiceless productions in singletons [$p < 0.001$] but not in geminates [$p = 0.14$]. It suggests that the durational difference of the release burst found between voiced and voiceless singletons (longer for voiceless and shorter for voiced) is largely cancelled in geminates (voiceless geminates do not have a longer release burst than voiced geminates). The same model of interaction was calculated for mean intensity of the release burst in dB (Fig. 5 bottom). The model yielded a significant result [$F(1, 36.91) = 17.77$, $p < 0.001$, $\eta_p^2 = 0.32$]. Post-hoc tests revealed that in the case of singletons, release intensity was significantly lower for voiced ($M = 37.6$, SE = 0.49) than for voiceless stops ($M = 40.1$, SE = 0.49) [$p < 0.001$]. The difference was largely cancelled in the case of geminates manifesting itself in a smaller and non-significant intensity difference between voiced ($M = 39.4$, SE = 0.62) and voiceless ($M = 41.5$, SE = 0.58) productions [$p = 0.51$].

Table 4. Means in millisecond and standard error for the closure duration and release duration in voiced and voiceless singletons across the three places of articulation.

	Voiced singletons				Voiceless singletons			
	Closure duration		Release duration		Closure duration		Release duration	
	M	SE	*M*	SE	*M*	SE	*M*	SE
Bilabial /b/	71.2	2.55	12.2	1.0	85.9	1.92	17.6	1.06
Dental /d/	53.5	2.12	12.9	0.61	69.4	2.0	21.8	1.02
Velar /g/	58.3	1.81	22.9	1.65	69.7	2.45	38.9	1.62

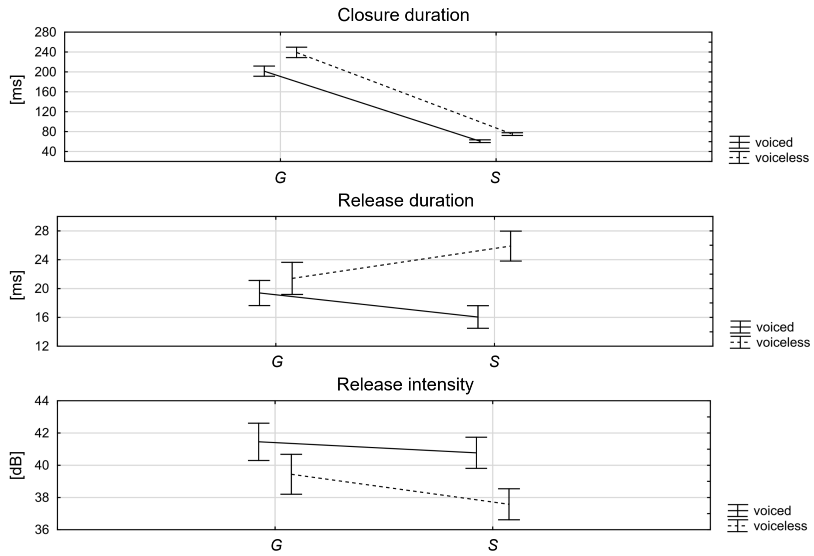

Fig. 5. Interactions between the singleton (S)/geminate (G) opposition and the voicing contrast (voiced – solid line, voiceless – dotted line) for closure duration in ms (top), release duration in ms (middle), and release intensity in dB (bottom). Whiskers = 0.95 CI.

6.3. Voicing in stop geminates: Case analysis

In this section, we discuss individual realizations of voicing that deserve attention in acoustic analysis. We are of opinion that automatic analyses of speech parameters by using scripts frequently lead to overlooking interesting instances of articulatory behavior. Our inspections of each individual production allowed us to isolate four different manifestations of voicing/devoicing in stop geminates other than what is typically reported in the literature. We will briefly discuss them in the following as they may be of interest for future studies investigating voicing in geminates or more generally in consonants.

Figure 6 shows waveform and spectrogram of an alveolar geminate /dd/ in the word *Upeddak* produced by Speaker 34 (female, age 20). Voicing in closure has two separate portions of almost equal durations, the first one has a duration of 84 ms and the second one of 77 ms. They are separated by an interval of voicelessness that lasts for 28 ms. A possible interpretation of this, apart from the physiological difficulty with maintaining longer periods of voicing in closure, is that it demonstrates underlying rearticulation of this geminate. Even though rearticulation does not emerge here in its standard manifestation of the release burst of the first consonant, it is signalled by the two separate voicing portions.

Figure 7 shows a bilabial geminate /bb/ in the word *Upebbak* produced by Speaker 7 (female, age 21).

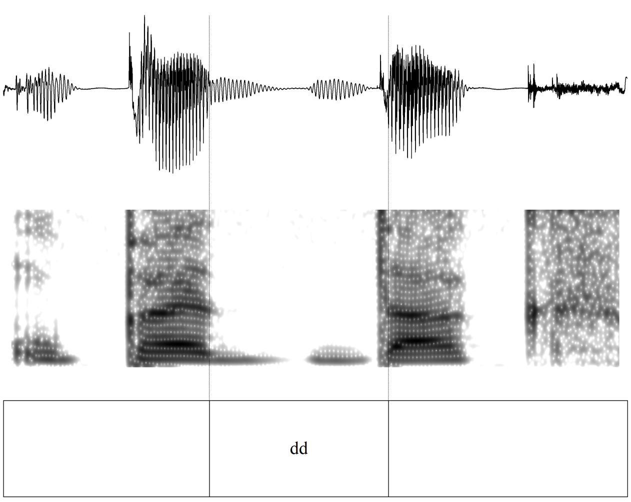

Fig. 6. Geminate /dd/ in the word *Upeddak* by Speaker 34 (female, age 20). Two visible portions of voicing separated by a period of voicelessness.

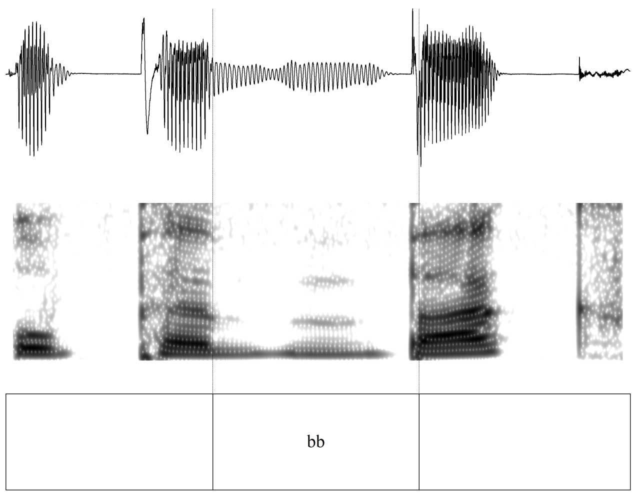

Fig. 7. Geminate /bb/ in the word *Upebbak* by Speaker 7 (female, age 21). Two visible portions of voicing differing in intensity followed by full devoicing prior to the release burst.

Voicing has two portions of intensity. The second portion with the duration of 139 ms is characterized by a rise in intensity compared to the first portion that lasts for 83 ms. There is an interval of full devoicing to the end of the geminate, prior to the release burst, that lasts for 25 ms. Such articulation with two separate portions of periodicity differing in magnitude may also suggest underlying rearticulation.

Figure 8 shows a bilabial geminate /bb/ in the word *Upebbak* produced by Speaker 41 (female, age 20). Closure duration has an observable division into two portions. The first portion with the duration of 114 ms is characterized by full voicing of very strong intensity. In the middle of the closure there is an abrupt cessation of voicing into the second portion that lasts for 100 ms and is completely devoiced. Such a realization may also be indicative of underlying rearticulation, suggesting a nonuniform status of a geminate that may be represented as /bp/. Naturally, as pointed out by a reviewer, such realizations are not uncommon in Japanese voiced geminates and may equally likely result from physiological reasons that we discuss in Introduction.

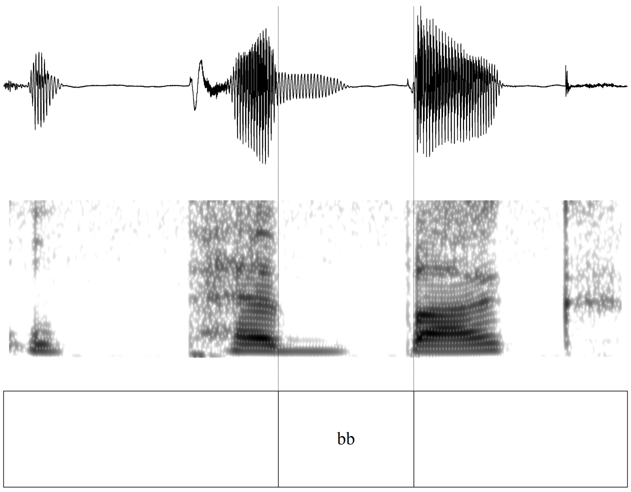

Fig. 8. Geminate /bb/ in the word *Upebbak* by Speaker 41 (female, age 20). The period of high-intensity voicing followed by abrupt complete devoicing.

Figure 9 shows a bilabial geminate /bb/ in the word *Upebbak* produced by Speaker 23 (female, age 20). In this case, devoicing is atypical, because normally devoiced stops have a period of voicing followed by voicelessness. Here, there is a period of long voicelessness in the onset portions of the consonant that lasts 254 ms followed by a sudden emergence of a short interval of voicing prior to the release with the duration of 58 ms. Interestingly, the auditory impression of this geminate is that it is almost fully voiced. One of the reasons for the "voiced" auditory impression may be a very abrupt energy rise at the onset of the vowel.

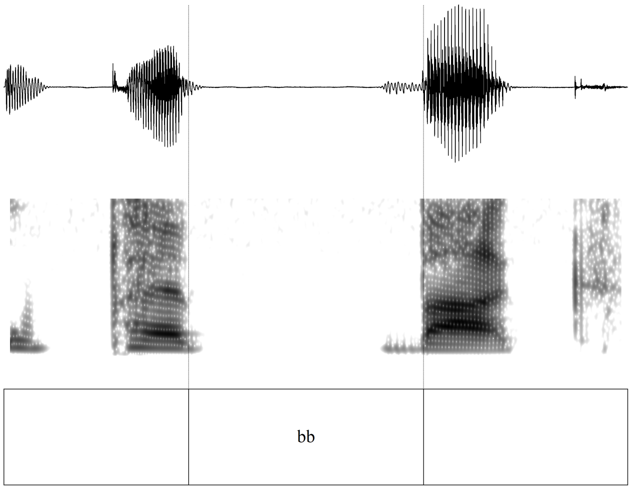

Fig. 9. Geminate /bb/ in the word *Upebbak* by Speaker 23 (female, age 20). Long portion of voicelessness followed by a sudden emergence of short voicing.

7. Discussion

The analysis of the collected data allows us to address aforementioned research issues.

Are Polish phonologically voiced geminates devoiced and what is the magnitude of devoicing?

Polish stop geminates have a mean voicing ratio of 0.69, which permits a conclusion that globally Polish stop geminates are partially devoiced. This locates Polish in the group of languages that devoice geminates fully or partially such as Japanese (Fujimoto, Kataoka, 2016; Hirose, Ashby, 2007; Hussain, Shinohara, 2019; Kawahara, 2006) or Tashlhiyt Berber (Ridouane, 2010), and in contrast to languages that retain voicing throughout the geminate closure such as Buginese (Cohn *et al.*, 1999) or Egyptian Arabic (Kawahara, 2006). Compared to Japanese, Polish geminates with the ratio of 0.69 may be referred to as mildly devoiced, because the voicing ratios in Japanese range, depending on the study, from 0.3 to 0.4 (Kawahara, 2006), 0.53 (Hirose, Ashby, 2007), or 0.2 to 0.25 (Hussain, Shinohara 2019). The results of our study and previous reports on geminate devoicing may explain why voiced geminates are considered to be typologically marked and appear less frequently in the world's languages than voiceless geminates (Ohala, 1983; Westbury, Keating, 1986; Blevins, 2004; Hayes, Steriade, 2004). Since global measures of devoicing, defined as the proportion of voicing duration to total closure duration, obscure the analysis of actual individual realizations, we provided quantification of the voicing ratio into three voicing groups: devoiced (0.00 to 0.49), partially devoiced (0.50 to 0.89), voiced (0.90 to 1.00). The distribution in these categories was relatively balanced (33 % of voiced, 38 % of partially devoiced, 29 % of devoiced productions). Polish stop singletons have a mean voicing ratio of 0.91, which is significantly higher than the one in geminates. This allows us to answer the question formulated in the title of the study concerning the amount of voicing in a geminate. The answer is that Polish phonologically voiced stop geminates are significantly less voiced than their corresponding singletons.

Is there observable speaker variability in the magnitude of devoicing?

There was an observable speaker-dependent variability in the realization of voicing. Only voiced geminates were produced by 14 % of the speakers, 20 % of the speakers fully devoiced all geminates, and 66 % of the speakers partially devoiced geminates in their speech. Such variability indicates that speakers differ in their voicing realizations and devoicing is not a uniform and omnipresent speech strategy for all speakers of Polish.

Is the duration of voicing correlated with the duration of the closure?

Since longer closure durations are not conducive to maintaining glottal activity necessary for voicing (Catford, 1977; Jaeger, 1978), it was hypothesized that shorter closures would predict more voicing, as formulated by the Aerodynamic Voicing Constraint (AVC) (Ohala, 1997), according to which longer closure favors devoicing due to balancing of air pressure in the sub- and supra-glottal cavities. The current results showed a trend in this direction ($b^* = -0.17$), however not at the level of statistical significance. The reason for the observed limited regression power may be the fact that the geminate/singleton contrast strongly relies on durational differences (Esposito, Di Benedetto, 1999; Kingston *et al.*, 2009; Amano, Hirata, 2010; Al-Tamimi, Khattab, 2018; Rojczyk, Porzuczek, 2019a). In more detail, even though shorter closure durations may promote more voicing in closure, geminates are restricted in the shortening of the closure portion at the pressure of remaining distinct from singletons. This hypothesis is supported by the fact that, as shown in this and other studies (Homma, 1981; Idemaru, Guion 2008; Al-Tamimi, Khattab, 2018), voiced geminates tend to be shorter than their voiceless counterparts. This shortening tendency may be motivated by the need to sustain voicing throughout closure to the maximum, however not at the expense of merging durationally with singletons. Another interpretation may be supported by studies showing that speakers do not necessarily have to rely on reducing closure duration to sustain voicing if they resort to other strategies to keep the voicing conditions effective such as lowering the larynx, advancing the tongue root, or raising the tongue and the soft palate with the aim of increasing the size of the pharyngeal cavity (Halle, Stevens, 1971; Westbury, 1983; Solé, 2009; Al-Tamimi, Khattab, 2018).

Is there interaction of voicing and the geminate/singleton contrast for closure duration, release duration and release intensity?

In terms of closure duration, both voiced geminates and singletons were significantly shorter than their voiceless counterparts, confirming previously cited reports that voicing is reflected in shorter closure durations. The interaction was contributed to by larger shortening effect for geminates (37 ms) than for singletons (14 ms). This difference is predictable on the grounds that longer durations of geminates provide them with more room for durational variability. This result stands in contrast to the results in (Butcher, 2004), who found shortening for voiced singletons only, but not for geminates, suggesting that the closure lengthening as a cue to gemination has a primacy over durational differences cuing the voicing contrast.

Duration of the release burst interacted significantly with the voiced/voiceless contrast and the singleton/geminate opposition in that the release duration differentiated voiced and voiceless categories in the case of singletons, but not in the case of geminates. Voiceless singletons had a significantly longer release burst than their voiced counterparts by 9.8 ms. This effect was not observed for geminates, suggesting that the voicing cue of release duration is neutralized in geminates, at least in the case of stop geminates in Polish. A similar interaction was found for intensity of the release burst. In the case of singletons, voiced productions had mean intensity of the release burst that was significantly lower (by 2.6 dB) than in corresponding voiceless productions. This difference was cancelled in geminates in which intensity of the release did not significantly differentiate between voiced and voiceless tokens. In general, these results show that the voiced/voiceless cues in the release burst, such as duration and intensity which are operative in singletons, are neutralized in geminates. It may suggest that the whole burden of cuing the voicing contrast in geminates relies on the closure duration and voicing in closure.

Are there atypical realizations of voicing in Polish stop geminates?

In the current results, we have isolated instances of atypical voicing realizations in Polish stop geminates. Although devoicing is commonly defined as gradual cessation of low-energy periodic signal towards the end of closure, some of the discussed realizations show divergent patterns. In the collected sample of Polish geminates, voicing may have two peaks separated by either an interval of weak voicing or complete voicelessness. We interpret these realizations as reflections of underlying rearticulation. Voicing may also emerge in the final portions of the closure preceded by voicelessness.

8. Conclusions

The long duration of geminate constriction facilitates a variety of phonetic effects related to the coordination of glottal and supraglottal articulatory gestures. Generally, considering the wide range of devoiced closure portion durations, and large inter-speaker variation, we may suggest little significance of true voicing for phonological voicing identification in Polish geminates or little communicative importance of such identification. The articulatory effort to maintain vocal fold activity throughout the constriction appears superfluous in contexts where no lexical ambiguity may be expected, and where other consonant clusters tend to assume a uniform phonation type. Similarly, the burst intensity level, whether or not actually used as a cue to voicing in singletons, is not modified systematically by speakers to cue the contrast in geminates, where it would also require more articulatory effort. Singletons, on the other hand, are characterized by more salient voicing in closure and burst length distinctions for the same two reasons that were signaled above. First, articulatory control of these features is easier in shorter constrictions, and second, possible voicing neutralization in singletons is more likely to trigger lexical identification problems.

Finally, the separate portions of voicing and abrupt voicing intensity changes within an individual closure presented in case analysis section, as well as the existence of rearticulation may give evidence to the hypothesis that Polish geminates may be regarded as biphonemic combinations. This idea deserves further phonological investigation, because it still needs to accommodate the majority of productions which are single-articulated and thus phonetically they fulfil the requirement of a long consonant similar to, e.g., Italian or Japanese. It is still not clear how geminates should be treated in various languages (the original term itself suggests two elements) and we believe that various empirical studies, including the present one, may help us better understand their nature.

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