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Temporal acoustic correlates of the voicing contrast in European Portuguese stops

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This study focuses on the temporal analysis of stops /p b t d k ɡ/ and devoicing analysis of voiced stops /b d ɡ/ produced in different word positions by six native speakers of European Portuguese. The study explores acoustic properties related to voicing. The following acoustic properties were measured: voice onset time (VOT), stop duration, closure duration, release duration, voicing into closure duration, duration of the preceding vowel and duration of the following vowel. Results suggested that when [b d ɡ] were devoiced, the acoustic properties stop duration, closure duration, duration of the following vowel, duration of the preceding vowel and duration of voicing into closure were relevant for the voicing distinction. Implications for research and practice in speech and language therapy are discussed. Further investigation is needed to find how the productions analysed in the present study were perceived by listeners, specifically productions of devoiced stops.

1 Introduction

There have been many studies of stop voicing distinctions (Caramazza & Yeni-Komshian 1974, Klatt 1975, Luce & Charles-Luce 1985, Cho & Ladefoged 1999, Brunner, Fuchs, Perrier & Kim 2003, van Alphen & Smits 2004), showing that the properties that are relevant vary across languages. However, there are few studies of European Portuguese (EP), none of which analyse the different stops in word-final position (Andrade 1980, Viana 1984, Veloso 1995, Castro & Barbosa 1996). This is a study of the voicing distinction and other production characteristics in EP using new detailed temporal descriptions and devoicing criteria.

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Lisker & Abramson (1964) found in a cross-linguistic study of word-initial position three categories of voice onset time (VOT): voicing lead (voiced), short lag (voiceless unaspirated) and long lag (voiceless aspirated). Keating, Linker & Huffman (1983) examined 51 languages and showed that the voiceless unaspirated category is the most common category. Almost all the studied languages used this category. The voiced and voiceless aspirated categories appeared equally frequently as the voicing category contrasting with the voiceless unaspirated category. Keating et al. (1983) also observed that the use of these different VOT categories varied as a function of word position in many languages.

Andrade (1980) compared the VOT of homorganic stops, in initial position before a vowel, in words produced by a speaker of EP. Results showed that some voiced stops had a period of prevoicing (between 120 and 130 ms) followed by a devoiced period (between 10 and 20 ms). Results also showed that the VOT was larger for velars than for labials and dentals, as in English (Klatt 1975, Cho & Ladefoged 1999). Viana (1984) concluded that [b d g] were sometimes devoiced in EP. Viana (1984) and Veloso (1995) observed that stop duration and duration of the following vowel were acoustic properties that cued voicing in EP.

Voicing of stops produced by speakers of various other languages have long been studied. Caramazza & Yeni-Komshian (1974) concluded that in Canadian French more than 58% of the voiced tokens were produced without prevoicing. Luce & Charles-Luce (1985) suggested that vowel duration was the most reliable correlate of voicing for stops in word-final position. The mean vowel duration was longer for words ending in voiced stops (177 ms) than those ending in voiceless stops (122 ms). Brunner et al. (2003) suggested other acoustic properties related to the voicing distinction for Korean velar stops in medial position, namely closure duration, duration of the following vowel, duration of the preceding vowel and voicing into closure duration. Van Alphen & Smits (2004) showed that stops were often devoiced in Dutch and that there were multiple acoustic properties related to the voicing distinction, e.g. the duration of prevoicing for both labial and alveolar stops, F0 movement for labials and the spectral centre of gravity of the burst for alveolars.

Vowel devoicing and deletion in EP, as well as the effect of deletion in the neighbouring segments, have been also studied for more than a century (Andrade 1994). Andrade (1993, 1995) presented acoustic and perceptual studies of CC stop clusters with equal and different places of articulation, as well as with and without an underlying vowel. Those studies provide important information on the effects of vowel devoicing and deletion on the temporal and spectral characteristics of the consonants. Moreover, in a sequence of two words, when the last syllable of the first word is identical or very similar to the first syllable of the second word, the final vowel of the former may be deleted and the two consonants may become a geminate or reduce to just one consonant. This phenomenon, known as syllable degemination (or haplology), was originally studied by Sá Nogueira (1938, 1941) and more recently re-analysed by Frota (2000) in the Prosodic Phonology framework. Frota (2000) showed, based on the analysis of spectrograms and auditory tests, that a C1V1C2V2[1] sequence reduces to C2V2 at prosodic word boundaries within a phonological phrase, to C1C2V2 at a phonological phrase boundary and remains as such at intonational phrase boundaries, where reduction is most disfavoured/blocked.

The principal aim of this study is to contribute to the knowledge of the acoustic properties related to the voicing distinction of stop consonants /p b t d k g/. So far, there have been no journal studies published about the production of EP stops, so there is a lack of reference data for normal cross-language studies, and no baseline data that can be used by Portuguese speech and language therapists in their clinical practice (e.g. VOT values could be used in the

[1] C1 = C2

differential diagnosis of different types of dysarthria, as reported for other languages) (Morris 1989, Ackermann & Hertrich 1997).[2]

In this study, the stops were produced in all word positions (initial, medial and final), as there is no research that has analysed EP stops in word-final position. An exhaustive temporal analysis was conducted (an EGG signal was used to determine voicing onset/offset) to obtain different acoustic properties (VOT, stop duration, closure duration, release duration, voicing into closure duration, duration of the preceding vowel and duration of the following vowel) in all word positions. Also, criteria that have been previously used for devoicing analysis of fricatives (Jesus & Shadle 2002, 2003; Jesus & Jackson 2008) were adapted to the study of stops.

2 Method

2.1 Recording and annotation

A corpus of 54 European Portuguese real words containing six stops, /p b t d k ɡ/, was recorded using a Philips SBC ME 400 unidirectional condenser microphone located 20 cm in front of the subject's mouth. An electroglottograph (EGG) signal was also collected using an EGG processor (model EG-PC3 produced by Tiger DRS, Inc., USA). The acoustic and EGG signals were pre-amplified (Rane MS 1-b) and recorded with a Sony PCM-R300 DAT recorder, each with 16 bits and a sampling frequency of 48 kHz.

The corpus contained an equal number of words (eighteen) with stops in three positions: initial position, followed by the vowels /a/, /i/ and /u/; medial position, preceded by the vowels /a/, /i/ and /u/ and followed by the vowel /ɐ/; and final position, preceded by the vowels /ɔ/ and /a/. The words were produced within the frame sentence *Diga ___ por favor*.[3] The words in the corpus are listed in the Appendix. The subjects were six native speakers of EP: three men – LJ (second author), HR and PA (aged 25–34 years) – and three women – ML (first author), IM and SC (aged 24–42) – all without any speech, language or hearing problems. LJ, HR, ML and IM lived in Aveiro, and PA and SC lived in Porto. In these regions, due to dialect characteristics, voiced stop consonants are often produced as non-strident continuants (fricated stops; Viana 1984, Cruz-Ferreira 1999). We used six stops in three word positions, produced by six speakers in a frame sentence.

The corpus was manually segmented with *Adobe Audition* 3.0. The words were then analysed using the *Speech Filing System* (*SFS*) version 4.7/Windows (Huckvale et al. 1987). The acoustic events that were annotated are listed here (see Figures 1 and 2).

1. The beginning of a preceding vowel (IV1) was defined using the following criterion: the instant in time at which the second formant intensity becomes characteristic for a vowel in the spectrogram (Brunner et al. 2003).[4] Figure 1 shows an example where this criterion was used (tokens where the EGG signal was clearly periodic before F2 onset). When the EGG signal was not periodic before F2 onset, IV1 was marked where the periodic signal begins both in the acoustic and EGG signals.
2. The end of a preceding vowel and beginning of closure (IO) was marked where the second formant was no longer visible in the spectrogram (Brunner et al. 2003). It was always

Q1 [2] The only related study published in a journal is that of Barroco, Domingues, Pires, Lousada & Jesus (2007). It analyses stops in two Portuguese children, one with speech disorders and one with normal speech.

[3] Sentences were produced with a pause between the end of the target word and the voiceless bilabial stop consonant that followed, so the carrier sentence did not have a direct impact on the duration measurements of the target stop consonants occurring in word-final position.

[4] The words were analysed using wideband spectrograms. The bandwidth for the wideband display was fixed at 300Hz.

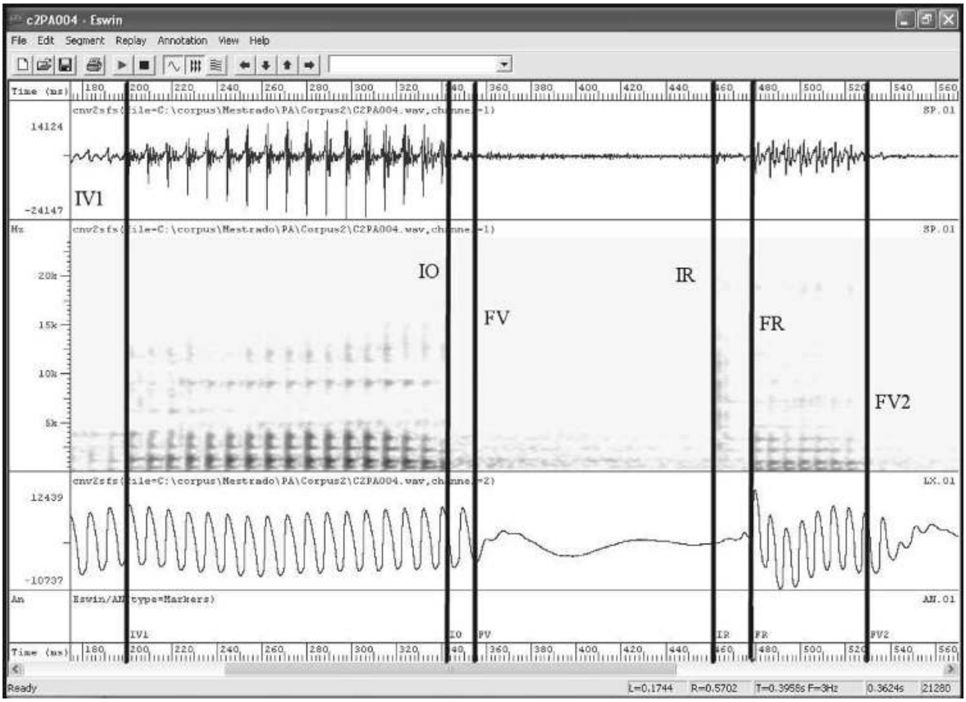

Figure 1 Waveform and its spectrogram, and EGG signal of the VCV sequence in the word [ˈnapɐ] ‘sheepskin’ produced by speaker PA.

possible to determine IO because the words were produced within a frame sentence, so even word-initial stops were preceded by a word that ended with a vowel.

3. The beginning of prevoicing (IPV) was defined as the instant in time at which evidence of vocal fold vibration could be observed in the acoustic and EGG signals (van Alphen & Smits 2004).
4. The voice offset (FV) was marked at the point where the periodic signal ends (the vocal folds ceased to vibrate) in the acoustic and EGG signals, as can be seen in Figure 1.
5. The end of prevoicing (FPV) was defined as the instant in time where the burst started.
6. The end of closure and the beginning of the release (IR) was defined by a sudden peak in the waveform and as a vertical bar in the spectrogram. When there were multiple bursts, the one with the highest intensity was chosen, as the one with the highest intensity is believed to correspond to the actual opening (Fuchs 2005).
7. The end of release and beginning of the following vowel (FR) was marked where the second formant amplitude begins in the spectrogram (Brunner et al. 2003) or where the periodic signal begins both in the acoustic and in the EGG signals.
8. The end of the following vowel (FV2) was set where the second formant was no longer visible in the spectrogram (Brunner et al. 2003).

In the annotation files, we also registered the position in the word (initial, medial and final) and the type of voicing according to new criteria based on those previously proposed for fricatives by Jesus & Shadle (2002):

- When voicing was present less than a third of the closure interval, the stop was classified as devoiced.

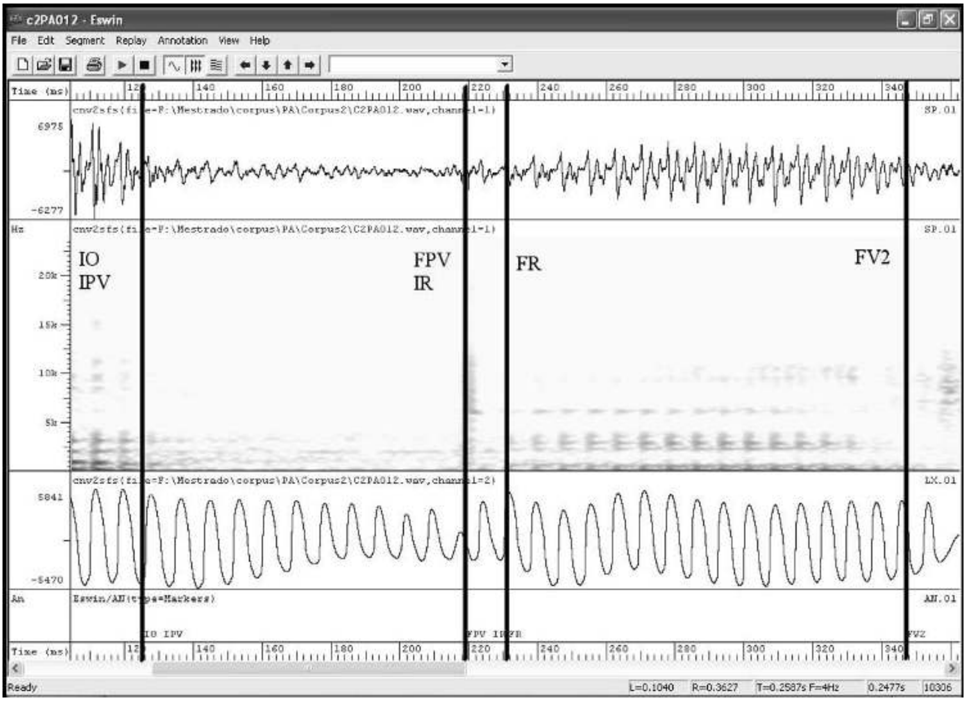

Figure 2 Waveform and its spectrogram, and EGG signal of the first CV sequence in the word [ˈbufu] 'owl' produced by speaker PA.

- When voicing lasted from between a third and a half of the closure duration, the stop was classified as partially devoiced.
- When the duration of voicing was greater than a half of the closure duration, the stop was classified as voiced.[5]

2.2 Temporal analysis

The following temporal measurements were extracted from the annotation files of the corpus for all speakers:

1. Duration of preceding vowel: IO-IV1.
2. Voicing into closure duration: FV-IO (for stops in medial and in final positions).
3. Closure duration: IR-IO.
4. Voice onset time (VOT): FR-IR (for voiceless, devoiced and partially devoiced stops) or IPV-IR (for voiced stops).
5. Release duration: FR-IR (positive VOT).
6. Duration of following vowel: FV2-FR.
7. Stop duration: FR-IO.

This list of temporal measures presents some redundancies (e.g. stop duration could be calculated through the duration of all components of the stop), but it allowed us to design an algorithm to automatically extract the durations, using *Matlab* scripts.

[5] These criteria are also used in Pinho, Jesus & Barney (2010).

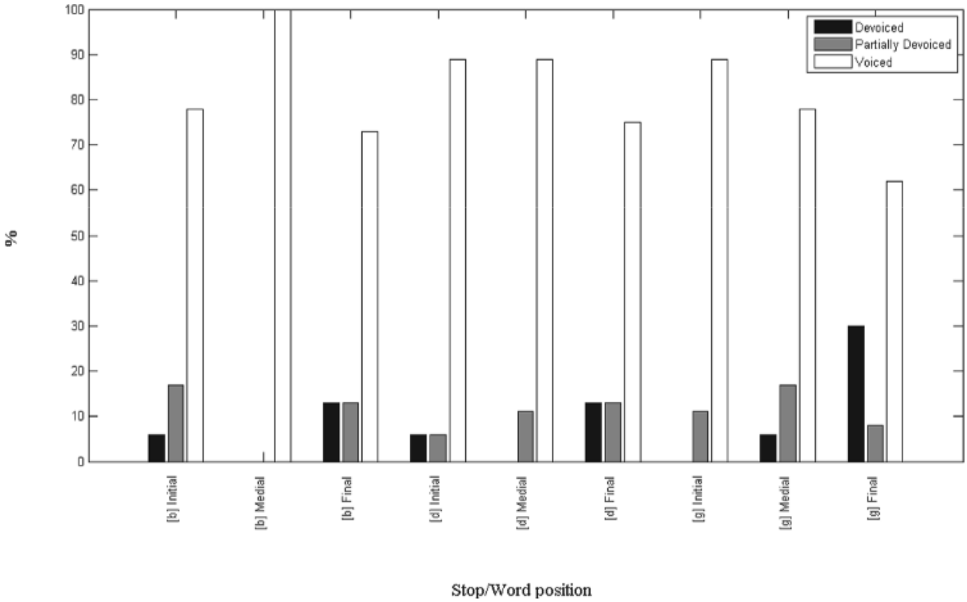

Figure 3 Devoicing of [b d g] for all speakers in different word positions.

2.3 Statistical tests

The software package SPSS 10.0 for Windows was used to run the statistical tests for stop durations. We first determined if the distribution was normal, based on the observation of histograms, analysis of QQ-plots of normal distribution and the results of both the Kolmogorov-Smirnov test with Lilliefors correction and Shapiro-Wilk test in initial, medial and final positions. The results refute the normality of the data for medial ($p < .05$) and final position ($p < .05$) so we used the Mann-Whitney U test to compare the groups (duration of voiceless stops vs. duration of voiced stops). This non-parametric test allows us to compare the means of two groups when the data are not normal.[6]

3 Results

3.1 Devoicing analysis

Results of devoicing as a function of place of articulation showed that in initial position, the percentage of devoiced stops was exactly the same for [b] and [d] and was zero for [g]. However, [g] was partially devoiced in some cases. The percentage of devoicing increased as the place of articulation moved posteriorly in medial position (see Figure 3). In word-final position, the percentage of devoiced stops was greater for [g] than for [b] and [d].

[6] The use of non-parametric statistical tests does not imply that sample means and standard deviations are meaningless. In addition, we provide the sample median as a complement to the traditional mean and standard deviation statistics. Since the size of the considered sample lies between 38 and 54, we believe that the goodness-of-fit test considered (Kolmogorov-Smirnov with Lilliefors correction and Shapiro-Wilk) is meaningful.

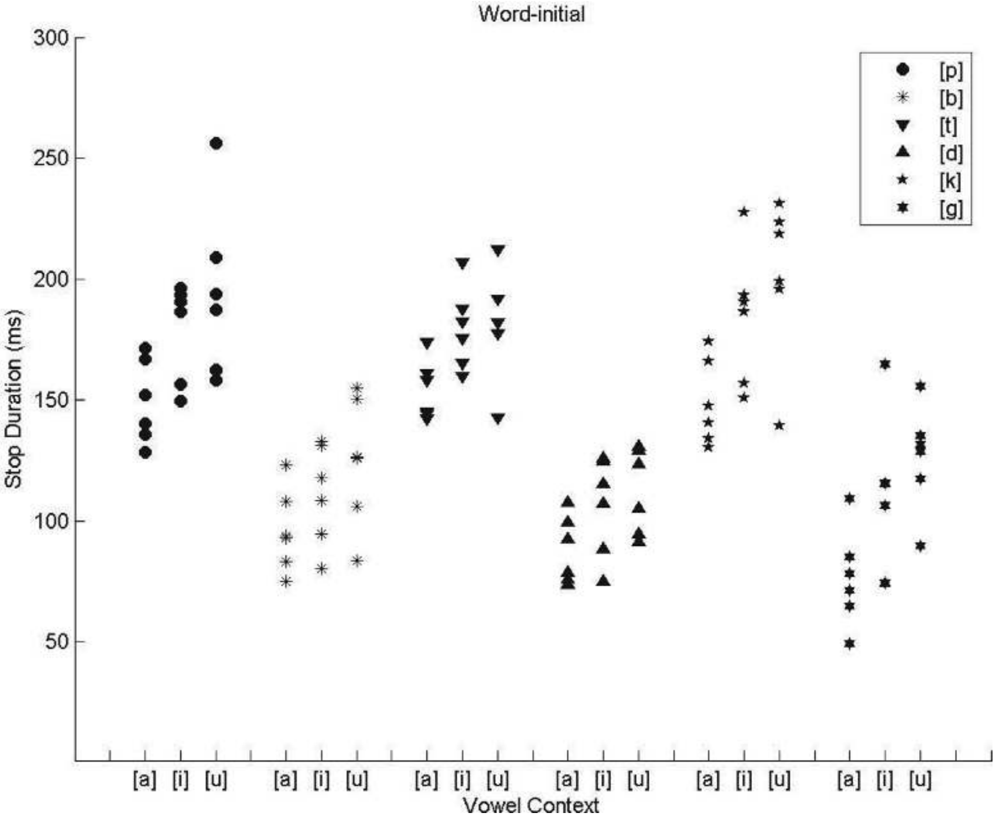

Figure 4 Stop duration of [p t k b d g] in initial position.

3.2 Temporal analysis

The results of stop duration, closure duration, release duration, duration of the preceding vowel and duration of the following vowel, voicing into closure duration, and VOT are presented separately in the following sections.

3.2.1 Stop duration

The mean duration (averaged over the six speakers) of stops in initial position was: 174 ms for [p], 173 ms for [t], 178 ms for [k], 111 ms for [b], 102 ms for [d] and 104 ms for [g]. Mean stop duration was longer for voiceless (mean = 175 ms, N = 54) than for voiced stops (mean = 106 ms, N = 54), as shown in Figure 4. For stops in medial position, the values were: 129 ms for [p], 135 ms for [t], 140 ms for [k], 74 ms for [b], 85 ms for [d] and 76 ms for [g]. Mean stop duration was longer for voiceless (mean = 134 ms, N = 54) than for voiced stops (mean = 78 ms, N = 53). In final position, the values were: 164 ms for [p], 176 ms for [t], 173 ms for [k], 131 ms for [b], 117 ms for [d] and 132 ms for [g]. Mean stop duration was also longer for voiceless (mean = 172 ms, N = 44) than for voiced stops (mean = 126 ms, N = 38). These differences were statistically significant ($p < .001$) using the Mann-Whitney U test. The analysis of the p-value of this test led us to conclude that there were significant differences between the duration of voiced stops and the duration of voiceless stops in initial, medial and final positions. The statistical tests were not applied for the other parameters because the database did not always provide more than 30 tokens in each group. This fact occurs for different reasons, e.g. the closure duration in some cases was not determined

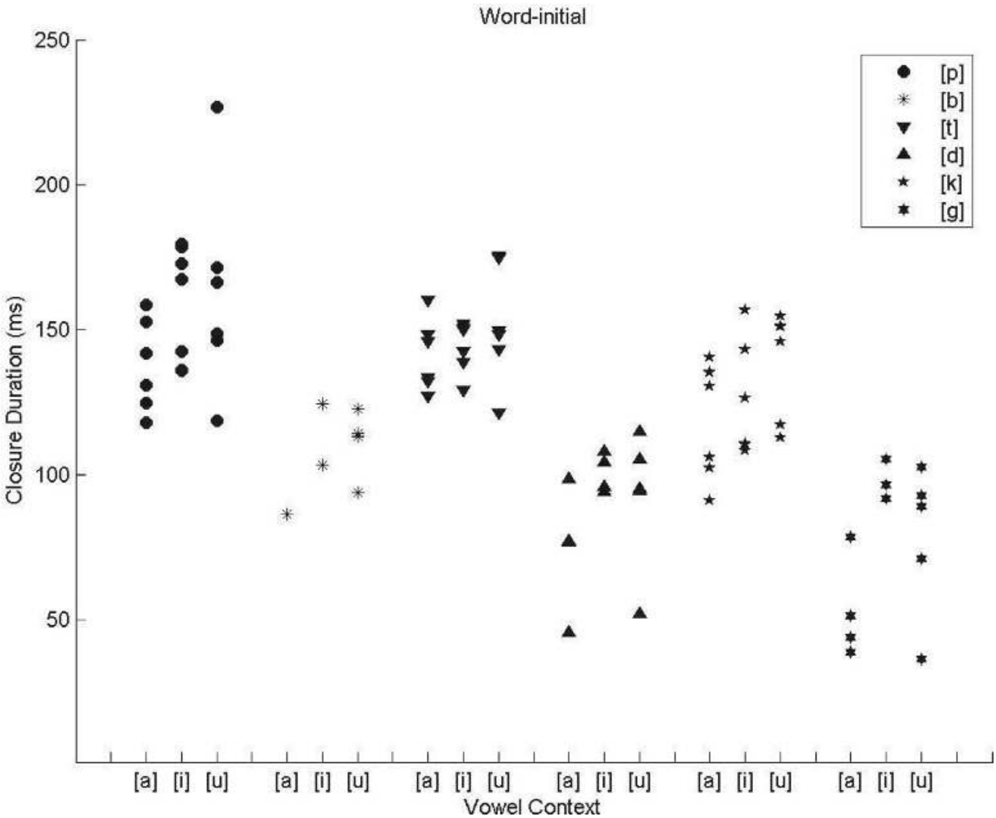

Figure 5 Closure duration of [p t k b d g] in initial position.

(it was impossible to determine the end of closure because many speakers produced the voiced stops without a release, particularly in medial and in final positions).

3.2.2 Closure duration

Mean closure duration of stops in initial position was: 155 ms for [p], 146 ms for [t], 128 ms for [k], 108 ms for [b], 90 ms for [d] and 75 ms for [g]. Mean closure duration was longer for voiceless (mean = 143 ms, N = 54) than for voiced stops (mean = 88 ms, N = 20), as can be seen in Figure 5. In medial position, the values of closure duration were: 110 ms for [p], 114 ms for [t], 104 ms for [k], 102 ms for [b], 57 ms for [d] and 79 ms for [g]. Mean closure duration was longer for voiceless (mean = 109 ms, N = 54) than for voiced stops (mean = 65 ms, N = 16). The values obtained for stops in final position were: 123 ms for [p], 131 ms for [t], 132 ms for [k], 90 ms for [b], 77 ms for [d] and 86 ms for [g]. Mean closure duration was longer for voiceless (mean = 129 ms, N = 44) than for voiced stops (mean = 82 ms, N = 21).

3.2.3 Release duration

The release duration was longer for voiceless (mean = 33 ms, N = 54) than for voiced stops (mean = 26 ms, N = 33) in initial position. In medial position the release duration was longer for voiced (mean = 32 ms, N = 17) than for voiceless stops (mean = 25 ms, N = 54). In final position the release duration was also longer for voiced (mean = 60 ms, N = 18) than for voiceless stops (mean = 43 ms, N = 44).

Table 1 Mean duration of the following vowel in the context of stops [p t k b d g] in initial position.

[a]	Mean (ms)	[i]	Mean (ms)	[u]	Mean (ms)
[pa]	121	[pi]	82	[pu]	83
[ta]	119	[ti]	63	[tu]	88
[ka]	105	[ki]	65	[ku]	90
[ba]	143	[bi]	82	[bu]	103
[da]	134	[di]	91	[du]	100
[ga]	134	[gi]	97	[gu]	115

Table 2 Mean duration of the preceding vowel in the context of stops [p t k b d g] in medial position.

[a]	Mean (ms)	[i]	Mean (ms)	[u]	Mean (ms)
[ap]	127	[ip]	87	[up]	81
[at]	128	[it]	84	[ut]	86
[ak]	125	[ik]	75	[uk]	88
[ab]	153	[ib]	88	[ub]	95
[ad]	159	[id]	106	[ud]	113
[ag]	156	[ig]	114	[ug]	119

3.2.4 Duration of vowels

The duration of the following vowel was longer in voiced–stop contexts (N = 54) than in voiceless–stop contexts (N = 54), when stops occurred in initial position, except for [pi] and [bi] (see Table 1) and in medial position. The duration of the preceding vowel was longer in voiced–stop contexts (N = 54 in both groups), when stops occurred in medial (see Table 2) and final positions.

3.2.5 Voicing into closure duration

The voicing into closure duration was longer for voiced (N = 10 in word-medial position and N = 23 in word-final position) than for voiceless stops (N = 54 in word-medial position and N = 52 in word-final position) in medial and word-final positions (see Figure 6). The voicing into closure duration in voiceless stops corresponds to the interval of time during which the vocal folds continue to vibrate so it is expected to be shorter for these stops.

3.2.6 VOT

In initial and medial position, voiceless stops had a positive VOT, and voiced stops had a negative VOT (fully voiced stops) or a positive VOT. The duration of positive VOT (averaged over all speakers, N = 18) in initial position was: 20 ms for [p], 28 ms for [t], 51 ms for [k], 28 ms for [b], 16 ms for [d] and 17 ms for [g]. Mean VOT duration for voiceless stops was 33 ms and mean VOT duration for voiced stops was 20 ms. The average values of negative VOT were: −114 ms for [b], −89 ms for [d] and −73 ms for [g] (mean [b d g] = −88 ms).

In medial position, the duration of positive VOT (averaged over all speakers, N = 18) was: 19 ms for [p], 22 ms for [t], 35 ms for [k], 33 ms for [d] and 38 ms for [g]. The mean value for [b] was not reported here because many speakers produced the stop without a burst (it was not possible to determine release onset). Mean VOT duration for voiceless stops was 25 ms, and mean VOT duration for voiced stops was 36 ms. The values of negative VOT were: −102 ms for [b] and −52 ms for [d] (mean [b d] = −59 ms).

Overall, VOT was on average shorter for [p] than for [t], and shorter for [t] than for [k] in initial and medial positions. In addition, VOT was on average longer before high vowels than before low vowels, which suggests that the VOT changed as a function of the characteristics of the following vowel (see Table 3).

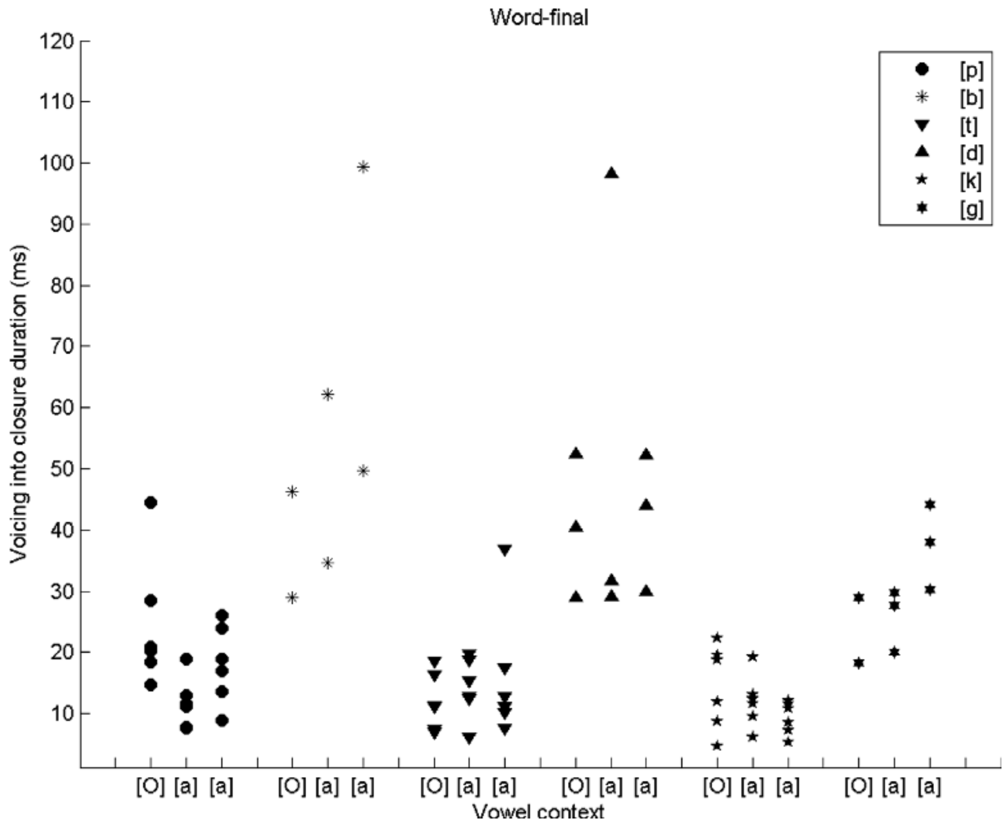

Figure 6 Voicing into closure duration of [p t k b d g] in final position.

Table 3 VOT in initial position as a function of the following vowel. Vowels are grouped in terms of their height.

Context	N	Mean (ms)	Standard deviation (ms)	Median (ms)
[pa]	6	12	2	11
[pi pu]	12	24	11	22
[ta]	6	13	1	13
[ti tu]	12	35	11	36
[ka]	6	31	8	32
[ki ku]	12	60	17	64

4 Discussion

This study examined the acoustic properties correlated with the voicing distinction, based on a corpus that included stops in different word positions, as a contribution to the acoustic description of EP stops.

The analysis of devoicing showed that stops [b d g] were sometimes partially devoiced or devoiced as reported previously for Canadian French (Caramazza & Yeni-Komshian 1974), EP (Andrade 1980, Viana 1984) and Dutch (van Alphen & Smits 2004). Vibration of the vocal folds can only occur when two physiological and aerodynamic conditions are met. First, the vocal folds must be adducted and tensed. Second, a sufficient transglottal pressure gradient is needed to cause enough positive airflow through the glottis to maintain vibration (van den

Berg 1958). There is a recognised difficulty in supporting vibration during stop production because the air flowing through the glottis accumulates in the oral cavity, causing oral pressure to approach subglottal pressure (Ohala 1983).

The results also showed that the percentage of devoicing increased as the place of articulation moved posteriorly except for stops in initial position. There is evidence that devoicing varies as function of place of articulation. Ohala (1983) has suggested that voiced velar stops are more easily devoiced than voiced stops produced at other places of articulation. This is due to aerodynamic reasons and to the net compliance of the surfaces on which oral air pressure impinges during the production of stops. In velar stops, only the pharyngeal walls and part of the soft palate can yield to the air pressure. In dentals, these surfaces plus the greater part of the tongue surfaces and all of the soft palate are involved. In labials, these surfaces plus all of the tongue surface and some parts of the cheeks participate (Rothenberg 1968).

In initial position, the mean stop duration was longer for voiceless (175 ms) than for voiced stops (106 ms). These results agree with those of Viana (1984) and Veloso (1995). In medial position, the stop duration was longer for voiceless (134 ms) than for voiced stops (78 ms). In final position, this measure was also longer for voiceless (172 ms) than for voiced stops (126 ms). The duration of the preceding vowel was longer in voiced stop contexts, when stops occurred in medial position, as shown previously by Brunner et al. (2003). The duration of the preceding vowel before voiced stops has been shown to be longer than before voiceless stops in English (Peterson & Lehiste 1960, Luce & Charles-Luce 1985). The mean closure duration in initial position was longer for voiceless (143 ms) than for voiced stops (88 ms) confirming the results reported by Viana (1984). In medial position, voiceless stops had longer closure durations (109 ms) than voiced stops (65 ms), as previously reported for Korean (Brunner et al. 2003). The closure duration was also longer for voiceless (129 ms) than for voiced stops (82 ms) in final position.

Longer vowel durations were accompanied by shorter closure durations for /b d g/ while shorter vowel durations were associated with longer closure durations for /p t k/. Kluender, Diehl & Wright (1988) have suggested an auditory explanation for these results. They have proposed that covariation of voicing correlates is planned to increase perceptual distinctiveness. Consequently, vowel duration differences serve to augment the distinctiveness of the closure duration cue to the voicing distinction. Long vowel durations preceding short closures result in the perception of even shorter closures, whereas short vowels preceding long closure intervals are perceived as longer closures. This auditory hypothesis suggested that speakers can exert control over the cues that have mutually reinforcing auditory effects to signal phonetic contrasts.

The release duration was longer for voiceless (33 ms) than for voiced stops (26 ms) in initial position, as in other studies of EP (Viana 1984) and in a study of Dutch (van Alphen & Smits 2004). In medial position, the release duration was longer for voiced (32 ms) than for voiceless stops (25 ms), which is not expected, although the number of occurrences of voiced stops was much lower than that of voiceless stops, to generalise these results. In final position, the release duration was also longer for voiced (60 ms) than for voiceless stops (43 ms).

The duration of the following vowel was longer in voiced stop contexts than in voiceless stop contexts, when stops occurred in initial and medial positions, confirming results from previous studies of EP (Viana 1984) and Korean (Brunner et al. 2003). The voicing into closure duration was longer for voiced than for voiceless stops in word-medial and word-final positions, as we expected. The results of voicing into closure duration for stops in medial position were similar to those presented by Brunner et al. (2003).

These results suggested that when [b d g] were devoiced, the acoustic properties stop duration, closure duration, duration of the following vowel, duration of the preceding vowel and duration of voicing into closure were relevant for the voicing distinction, and not only the two properties (stop duration and duration of the following vowel) that have been previously proposed for EP (Viana 1984, Veloso 1995). Perceptual tests are needed to complement our data to reveal how the productions of the present study were perceived by listeners, e.g. in devoiced stops.

Results also showed that many voiced stops were produced without a release particularly in medial and in final positions. This can be due to the fact that voiced stops may be produced as non-strident continuants (fricated stops), which often occurs in some speakers' regions. These fricated stops may be characterised by weak friction noise or by a transitional approximant-like formant structure, depending on the surrounding segmental and prosodic context. Frication of stops is most favoured in word-medial position (Viana 1984, Cruz-Ferreira 1999). Concerning final position, release can also be missing because a stop followed by another stop ([p] of *por favor* in the second part of the frame sentence) may be unreleased (Andrade 1994).

Results confirmed that place of articulation and VOT were related (VOT was longer for [k] than for [t] and [p]), as previously reported by Klatt (1975), Andrade (1980), Viana (1984) and Cho & Ladefoged (1999). In velar stops, the volume of the cavity behind the point of constriction is relatively smaller than in bilabial and dental stops, and this causes a greater pressure, which will take longer to fall, allowing adequate transglottal pressure for the beginning of vocal fold vibration (Cho & Ladefoged 1999: 209). This could explain why the VOT was longer for [k] than for [t] and [p]. The volume of the cavity in front of the point of constriction is greater in velar stops than in bilabial and dental stops, and this causes a greater obstruction to the release of the pressure behind the velar stop; thus this pressure will take longer to fall, provoking a delay in the production of adequate transglottal pressure (Cho & Ladefoged 1999: 209), also resulting in a longer VOT for [k] than for [t] and [p]. A faster articulatory velocity in bilabials (movement of the lips) than in velars (movement of tongue dorsum) allows a more rapid decrease in the pressure behind the closure and consequently a shorter time before an appropriate transglottal pressure (Cho & Ladefoged 1999: 210), which results in a shorter VOT for [p] than for [k]. Results also indicate that the VOT changed as a function of the characteristics of the following vowel, as previously observed by Klatt (1975) and Viana (1984).

Results show that the stops /b d g/ in EP are generally fully voiced (see Figure 3). Voiceless stops /p t k/ are unaspirated, as in French, Spanish, Italian and many other Romance languages (Ladefoged 2006: 148), making the stop /p/ of these languages similar to English initial /b/. The VOT data presented in this study complement previous studies (Lisker & Abramson 1964, Keating et al. 1983) that compare VOT in different languages.

5 Conclusions

Until now, studies of Portuguese stops have been few and limited. The analysis of EP stops in different word positions contributes to the acoustic phonetic description of EP stops. The devoicing analysis and the detailed temporal description used in this work are also new for EP stops. The data obtained in the present study could now be used by Portuguese speech and language therapists, namely VOT values could be used in the differential diagnosis of types of dysarthria, as previously reported in other studies (Morris 1989, Ackermann & Hertrich 1997), and devoicing values could also be used as reference data to compare with dysarthric patients who usually devoice consonants, particularly in word-final position (Scott & Ringel 1971, Platt, Andrews & Howie 1980).

The criteria adapted from Jesus & Shadle (2002) are a new, useful and practical method to analyse devoicing in stops. These criteria have been applied to the analysis of stops for the first time in the current study and have been applied in other studies (Barroco et al. 2007, Pinho, Jesus & Barney 2010) for normal and disordered speech. The exhaustive temporal description presented in this study allows analysis of different acoustic events that are relevant to the voicing distinction in stops when these consonants are devoiced.

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Appendix. Corpus used for the experiments

The transcriptions using the International Phonetic Alphabet (IPA) were adapted from the illustration proposed by Cruz-Ferreira (1999) for European Portuguese.

Table A1 Words of corpus with stops /p b/ in initial, medial and final position.

Stop	Position	Word	IPA
		pato	[ˈpatu]
	Initial	pico	[ˈpiku]
		pufo	[ˈpufu]
		napa	[ˈnapɐ]
/p/	Medial	ripa	[ˈripɐ]
		lupa	[ˈlupɐ]
		top	[ˈtɔp]
	Final	pape	[ˈpap]
		tape	[ˈtap]
		bato	[ˈbatu]
	Initial	bico	[ˈbiku]
		bufo	[ˈbufu]
		naba	[ˈnabɐ]
/b/	Medial	chiba	[ˈʃibɐ]
		juba	[ˈʒubɐ]
		sobe	[ˈsɔb]
	Final	sabe	[ˈsab]
		cabe	[ˈkab]

Table A2 Words of corpus with stops /t d/ in initial, medial and final position.

Stop	Position	Word	IPA
		tacto	[ˈtatu]
	Initial	tica	[ˈtikɐ]
		tuna	[ˈtunɐ]
		nata	[ˈnatɐ]
/t/	Medial	Rita	[ˈritɐ]
		luta	[ˈlutɐ]
		pote	[ˈpɔt]
	Final	bate	[ˈbat]
		date	[ˈdat]
		dato	[ˈdatu]
	Initial	dica	[ˈdikɐ]
		duna	[ˈdunɐ]
		nada	[ˈnadɐ]
/d/	Medial	vida	[ˈvidɐ]
		buda	[ˈbudɐ]
		pode	[ˈpɔd]
	Final	nade	[ˈnad]
		jade	[ˈʒad]

Table A3 Words of corpus with stops /k g/ in initial, medial and final position.

Stop	Position	Word	IPA
		cacto	[ˈkatu]
	Initial	quita	[ˈkitɐ]
		cume	[ˈkum]
		vaca	[ˈvakɐ]
/k/	Medial	pica	[ˈpikɐ]
		nuca	[ˈnukɐ]
		Roque	[ˈrɔk]
	Final	saque	[ˈsak]
		taque	[ˈtak]
		gato	[ˈgatu]
	Initial	guita	[ˈgitɐ]
		gume	[ˈgum]
		vaga	[ˈvagɐ]
/g/	Medial	viga	[ˈvigɐ]
		guga	[ˈgugɐ]
		rogue	[ˈrɔg]
	Final	pague	[ˈpag]
		vague	[ˈvag]

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