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Patterns in allophone distribution for voiced and voiceless stops

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Abstract: Do languages prefer certain types of stop consonants in certain environments? A survey of 51 languages reveals two general trends. First, many languages limit the occurrence of final stops; final devoicing is one instance of this phenomenon. Second, other variation is largely limited to languages whose contrasts in initial position involve short lag vs. long lag VOT; that is, aspiration contrasts. Among these languages, many sorts of variation are found, which therefore must be described by language-specific rules.

It has often been observed that languages prefer voiceless over voiced consonants. At the same time, however, it is generally thought that intervocalic consonants will most naturally be voiced. If this is indeed the case, then we should see either consistent patterns of contrast neutralization, or of allophonic variation, with voiceless consonants being found everywhere except intervocally. Work with an aerodynamic model (Westbury & Keating, 1980, and further work) leads one to expect just that: voiceless unaspirated initial and final stops but voiced medial stops. Nonetheless, data from natural languages does not appear to lend overwhelming support to these predictions, particularly in terms of medial voicing (Houlihan 1982). It became clear to us that better data on positional variation in consonant voicing was required to compare with results from physiological modeling studies. Therefore we began a survey of the allophones of voiced and voiceless stop phonemes in various languages.

Allophone survey

The languages surveyed include those in Lisker & Abramson's (1964) study of word-initial VOT values, and the various languages whose initial VOT values have been similarly determined since then. These languages form less than half the database. Additional languages were added to increase the overall variety, both genetic and phonetic, of the database, and to provide sufficient examples of phenomena of particular interest. All stop consonants, including glottalic segments, were included in the survey. The data consist primarily of statements about allophone and phoneme distribution, largely derived from impressionistic transcriptions used for classical phonemicizations. In many cases the sources consulted are those used in compiling the UCLA Phonological Segment Inventory Database (UPSID, Maddieson 1981), a listing of the phonetic feature description of one principle allophone for each of the surface phonemes in 317 languages. UPSID was designed precisely to abstract away from the kind of positional variation that we are interested in, but its sources were often well suited to answering our questions. However, just as often such sources do not

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consider a sufficiently wide range of environments, and so where possible we supplemented information from the literature with our own or others' acoustic measurements, and with information from UCLA student phonetic projects and field notes. The major sources consulted and the allophones that were found are described for each language in the Appendix. Here we will describe the relevant trends observed across these data.

A major, though expected, trend across languages is the overwhelming preference for voiceless unaspirated stops. All of the languages surveyed except Bobo, Breton, and possibly Yidiɲ use at least this category.* Languages with a [voice] contrast generally use the voiceless unaspirated category in opposition to one or more other categories; exceptions include various languages with a [b] but no [p]. Beyond this preference, variation across positions in a word is also found. In the discussion that follows, we will focus on two kinds of variation: first, restrictions on final consonants, which are found in languages with all kinds of voicing contrasts, and restrictions on medial consonants, which hold largely of languages with initial aspiration contrasts.

Languages limit the consonants that can occur in final position to a greater or lesser extent. Some languages simply disallow final consonants, at least phonetically: Alyawarra (with a consistent final [ə]), Bobo, Kaititj, Kikuyu, Tiwi, marginally Hawaiian, with a final [ʔ], and Swahili, with final consonants only in loans. Other languages restrict final consonants to sonorants of one sort or another: Akan, Japanese, Mandarin, Tamil, Tswana, and Yidiɲ. Hausa allows final sonorants, and rarely [s], as well as having phonetic [ʔ] after short vowels. Spanish limits its final consonants to continuants. More common, however, is that stops are allowed but restricted in their manner. So, for example, Tagalog typically has unreleased final stops; English and Choctaw have optionally unreleased final stops. Burmese allows final nasals and a phonemic glottal stop /ʔ/ which in phrases may have various assimilatory phonetic realizations. Probably the best known type of final stop restriction is that final stops must be voiceless: Basque, Bulgarian, Cantonese, Choctaw, Dutch, Efik, Ewondo, Finnish, Gaelic, German, Polish, Russian, and Zoque. The voiceless stop restriction may, but need not, involve a synchronic phonological rule of final devoicing. It should be noted, however, that the phonological domain varies: in German it is syllable-final stops that are voiceless, while in Polish it is phrase-final stops. (Word-final but phrase-medial Polish voiceless stops can actually voice in some dialects (Mikoś, 1977).) A few languages have only unreleased *and* voiceless final stops: Korean, Nama, Thai, Tikar, Vietnamese. Thus it can be seen that "final devoicing" is just part of a larger trend to fewer segments and contrasts in final position. Other languages surveyed either have the same segments finally as initially and medially, or variation that involves, e.g., spirantization as part of the phonological contrast. Note that languages with four contrasting categories, e.g. Bengali, Hindi, Marathi, generally allow them all in final position, although not always in colloquial speech; Armenian and Tzeltal with three categories also allow them all in final position. Thus, while there is clearly a trend towards fewer contrasts in final position (involving other features such as place of articulation as well), and some variation in the allophones of the contrasting phonemes, it is certainly possible to sustain as many contrasts finally as elsewhere.

The situation for medial position is quite different, with variation being largely limited

*UPSID does contain a few examples of languages with voiced but no voiceless stops, but they were not included in our sample. Such descriptions are open to reinterpretation in light of the typical transcription of short lag VOT stops (voiceless unaspirated) as voiced, following English. The description of Yidiɲ makes such a reinterpretation likely but not certain.

to one particular kind. Recall that one motivation for this study was an interest in the occurrence of medial voiced stops. If phonetically voiced stops are found in initial position, it is almost always in contrast with some other category. In this case, a "preference" for voiced stops in medial position would have to involve neutralization of the contrast to a voiced variant. As noted before by Houlihan & Iverson (1979), languages typically do not have neutralization in medial position. On the other hand, if voiced stops do not occur in initial position, they could be found in medial position through allophonic variation in some category that does occur initially. First, a language with no voicing contrast could have voiced stops medially but voiceless stops elsewhere. We would in fact expect this to be the general pattern for languages without a contrast. Second, a language with an initial contrast between phonetically voiced and voiceless unaspirated stops could have a rule that changed the medial [+voice] stops into, e.g., fricatives, and [−voice] stops into voiced stops. Third, a language with an initial contrast between voiceless unaspirated and aspirated stops (e.g. most Germanic and Chinese languages) could have a rule that voiced one of those categories in medial position. Let us examine the data for each of these possible sources of medial voiced stops.

A reasonable hypothesis would be that languages without a [voice] contrast should show more allophonic variation than languages with a contrast, since a contrast might be thought to constrain possible variation within the phonetic space. Of the six languages without a contrast in our sample, only one is described as having a phonetic difference between initial and medial position: Yidiɲ appears to have systematic medial voicing, as predicted. However, none of the other five are described in this way. Spectrograms from one speaker of each language indicate that in Hawaiian medial stops are less aspirated than initial stops though they may have noise during the closure, while in Alyawarra (an Arandic language of Australia) medial stops are if anything slightly more aspirated than initial stops. Kaititj (related to Alyawarra) shows no systematic differences, and Tiwi (also in Australia) is explicitly described as having no intervocalic voicing. Nama (a Khoisan language of Africa) voices /t/ and /k/ after rising tones, but these segments only occur word-initially; labials, which do occur medially and finally as well, do not undergo this change. Overall, then, these languages show surprisingly little allophonic variation, and what there is, is not consistent across the six languages.

To this number can be added four languages with rather marginal voicing contrasts. Finnish's only voiced stop, /d/, occurs only medially, and even then only as a product of gradation rules. In addition, Suomi (1980) describes Finnish /p t k/ as often "voiced" intervocalically, but his own measurements show only a small amount of closure voicing. Next, the contrast in Kikuyu involves prenasalization as well as voicing, and there is no difference described between initial and medial positions. Third, in Cuna the initial voiceless unaspirated [p t k] are not part of a [voice] contrast, but in medial position they become voiced and contrast with voiceless geminates [pː tː kː]. Similarly, Tamil has no initial contrast but a medial contrast of short voiced stops (or fricatives) and geminate voiceless stops. Lastly, Choctaw's [voice] contrast is found only for labials; for all of its places of articulation, medial stops before unstressed vowels can be voiced. Again, then, there is some evidence for a preference for medial voiced stops, but no universal trend.

Languages with three or more contrasting categories in initial position often have the same categories in medial position (Bengali, Hausa, Marathi, Thai). However, Korean is a classical example of allophonic medial voicing, with initial [p t k] but medial [b d g]. E. Armenian is described as having a slight phonetic difference, with /b d g/ being more voiced medially, and possibly finally, than initially. Tikar has allophonic prenasalization, and Tzeltal has allophonic spirantization, of its medial [+voice] stops, with the other categories unchanged. Interestingly, Swahili is described as being in the process of eliminating its aspiration contrast by associating aspiration with initial position and with stress, a correlation that will re-appear below. Finally, word-initial voiceless unaspirated and aspirated stops in Burmese can become voiced in phrases, especially after a "weakened" (toneless and reduced) syllable. The initial consonant in the weakened syllable is then itself eligible for voicing. That is, Burmese voicing is a phrasal rule, somewhat like Polish voicing of word-final stops before a vowel-initiated word.

Languages with two contrasting categories in initial position, one voiced and one voiceless, and neither of which is aspirated, are languages with traditional "voicing" contrasts (Arabic, Basque, Bulgarian, Dutch, Efik, Ewondo, French, Japanese, Polish, Russian, Spanish, Tagalog, Zoque). Their VOT values in initial position, where ascertained, are seen to be lead *vs* short lag (Yeni-Komshian, Caramazza & Preston, 1977; Lisker & Abramson, 1964; Caramazza & Yeni-Komshian, 1974; Shimizu, 1979; Keating, Mikoś & Ganong 1981; unpublished UCLA data). Of these languages, only Efik, Ewondo and Spanish show any real differences between initial and medial positions, and these differences do not just involve voicing. Efik medial alveolars become flaps, and Ewondo [+voice] stops may become continuants, as they do in Spanish. However, even in these cases where the [+voice] stops become something else, the [−voice] stops remain voiceless and unaspirated (cf. Dent, 1976, on Spanish). Overall, there is little variation across these positions in these languages, and no tendency towards medial voicing, devoicing, or aspiration.

In contrast, languages whose initial stop contrast involves aspiration have been found to contrast short lag with long lag VOT values (Lisker & Abramson, 1964; Fischer-Jørgensen, 1954; Keating, 1983). These languages generally do show differences between initial and medial position. The most common pattern across languages involves medial deaspiration of initial voiceless aspirated stops, and/or medial voicing of initial voiceless unaspirated stops. Degree of stress is often implicated in descriptions of this pattern: English, Gaelic, Hindi, Kirghiz, Mandarin, Swedish, and sometimes German, are described as having unaspirated [−voice] stops before unstressed vowels. Mandarin, and sometimes German, are described as having voiced [+voice] stops before unstressed vowels. Choctaw, English, Kirghiz, Norwegian, Persian, Swedish, and Yidiɲ are all described as having voiced [+voice] medial stops, but not specifically before unstressed vowels. Danish treats medial stops differently, with spirantization of the [+voice] stops and voicing of the [−voice] stops. Akan and Cantonese are exceptions in that they appear to have no variation across positions.

In many of these cases, a sufficiently wide range of environments was not covered in the sources for us to be sure of the importance of stress as a conditioning factor. To clarify just two such cases, we collected acoustic data on English and Swedish, both languages with initial aspiration contrasts. While these are both Germanic languages, we emphasize that the phenomena of interest are not limited to such languages, as can be seen from the examples just given.

Acoustic data

Because a correlation between stress and phonetic detail was strongly indicated, we systematically varied both position in the word, that is, initial *vs* medial, and stress, that is, main stress *vs* other degrees of stress on a following vowel, for stops in each language. [illegible] half dozen real words were used for each position + stress condition. All stops occurred before low vowels, but the vowel before each stop was not controlled. Words were read in isolation, so all initial stops were post-pausal. Six speakers of each language read their list once in a

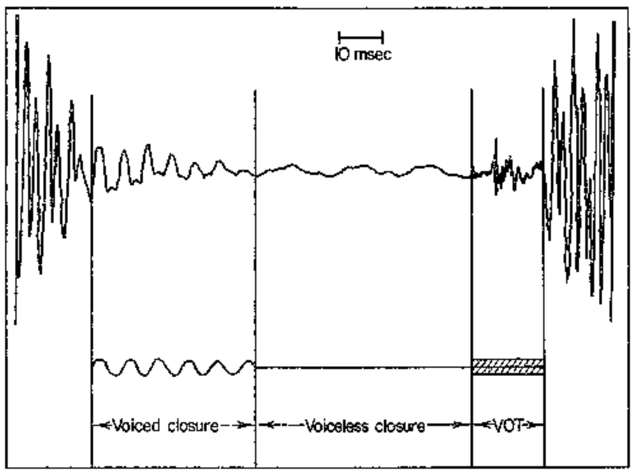

Figure 1 Acoustic measurements made for English and Swedish stops.

sound-treated booth. The items were not randomized, so as to make implicitly clear the desired stress contour. However, neither the experimental goals nor the lists were described to or discussed with the speakers.

Three measurements were made for each stop, shown in Figure 1. The top picture is a real waveform of the sort measured in a computer display; it includes some typical low-frequency noise that must be ignored. The point of closure in the waveform displays was determined on the basis of both a sudden decrease in amplitude, and a loss of frequency components corresponding to F2 and higher. Closure voicing containing energy at the fundamental frequency and sometimes F1 typically continued past the point of closure for at least one or two pitch periods. The moments of stop release and of voicing onset were determined in the usual ways. Below the waveform is a schematic version of the type we will use in presenting our results, and on the bottom is an indication of the measurements we made. The first was the duration of any voicing during closure, the second was the duration of voicelessness during closure, where that could be measured from an acoustic display. The sum of these two measures is the total closure duration. The third measure was the duration of voicelessness after the release, that is, lag VOT.

Results for English are shown in Figure 2. This experiment is similar to others in the literature (e.g. Lisker & Abramson, 1964, 1967; Flege & Brown, 1982), but it has the advantage of using the same speakers in a variety of contexts. For our speakers, while initial /b d g/ are generally voiceless and unaspirated, some speakers sometimes prevoice. Second, medial /p t k/ before reduced vowels generally have much lower VOT's, that is, are unaspirated. At the same time, medial /b d g/ are typically voiced, no matter what stress the following vowel has. However, for some speakers there is proportionately less voicing for /b/ (a surprising result) and/or before a syllable with main stress.

Results for Swedish are shown in Figure 3. The categories we tested were divided according to word accents, which require some explanation. A Swedish word has one of two pitch accents, which in the Stockholm dialect are markedly different from each other. Accent 1 words have one pitch peak, while Accent 2 words have two pitch peaks, one on each syllable. Only Accent 1 words can vary in where the stress falls; traditionally Accent 2 words are described as having primary stress on the first syllable and secondary stress on the second syllable. Therefore we separated Accent 1 from Accent 2 words in our list. Since our results

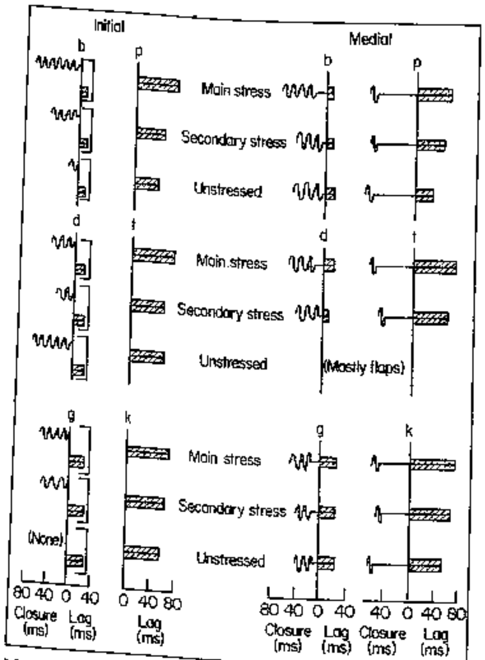

Figure 2 Mean acoustic measurements for English stops of six speakers. Initial b, d, g are divided into prevoiced and short lag groups.

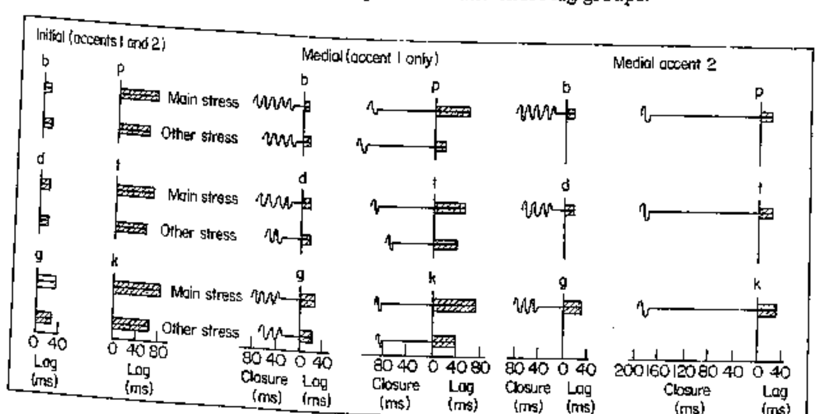

Figure 3 Mean acoustic measurements for Swedish stops of six speakers.

show that as far as VOT is concerned, stops in Accent 2 words look like the corresponding unstressed stops in Accent 1 words, we have collapsed these categories for initial stops. The closure voicing of these categories is also the same. However, since stops in Accent 2 words have much longer voiceless intervals during their closures, we have not collapsed these categories in our presentation of the medial data. Medial Accent 2 data are shown separately in Figure 3, although in their VOT values they behave like unstressed Accent 1 stops.

To summarize the overall Swedish results, initial /b d g/ do not have closure voicing while medial /b d g/ do, with stress having only slight effects. Initial /p t k/ are aspirated, as are medial /p t k/ before main stress. However, *other* medial /p t k/ are generally unaspirated. These data are like those of Löfqvist (1976) in which four speakers read nonsense words containing the stop consonants combined with /a/ in various stress and position contexts.

Our interest here has been grosser, categorial changes of the sort that might be noted in an impressionistic transcription and codified in a phonetic alphabet. However, various other effects of these variables on these measures have been the objects of others' investigations (e.g. Zue, 1976; Flege & Brown 1982). To some extent the patterns noted in those studies are seen here as well, but not always. However, we cannot expect to see effects on closure measures clearly, since the vowel preceding medial stops in our lists was not controlled. Nonetheless, we note briefly the effects evident in our data. For English, we see that stress increases the VOT for /p t k/; that place of articulation affects VOT, particularly for /b d g/. Place of articulation also affects the duration of closure voicing and the total closure duration; to a lesser extent the voicelessness measures, closure voicelessness and total voicelessness. Stress affects the duration of closure voicelessness for /b d g/, and of total voicelessness for all stops. For Swedish, the VOT measures are affected as for English. Also as for English, place of articulation affects the duration of closure voicing and for /b d g/ of total voicelessness. Stress affects the duration of closure voicing, for /b d g/ total closure, and for /p t k/ total voicelessness.

Discussion

To summarize, there is a clear overall trend in these languages to maintain aspirated /p t k/ before more stressed vowels, and to voice medial /b d g/. At the same time, there are differences between these two quite similar languages. While prevoicing is seen in English, it is at best rare in Swedish. There is also more variation across speakers in English regarding amount of medial voicing. In addition, there are differences with regard to closure durations, especially as conditioned by the pitch accents in Swedish.

Our language survey suggested a generalization that languages with initial "aspiration" contrasts account for most of the allophonic differences seen between initial and medial stops. This variation appeared to be correlated with stress. In the two languages considered here in some detail, there is remarkable agreement in how stops vary across contexts, with position determining /b d g/ allophones, and position plus stress determining /p t k/ allophones. To the extent that this pattern holds across a variety of languages, and is not due to the genetic relation between English and Swedish, then it can be attributed to some general phonetic principle. The small-scale effects of place of articulation and stress that were observed may also reflect some universal pattern. Variation due to universal principles need not be accounted for in the grammar of any one language; in further work we can attempt to elucidate these principles, e.g. by aerodynamic modeling.

However, there are also subtle differences between the two languages, in terms of category use, exact VOT values, amount of variation across speakers, and closure durations. Such quantitative differences apparently can not be attributed to universal principles, and, as part of speakers' knowledge of their language, must be represented somewhere in their grammars. That is, the very lowest level of the grammar must contain language-specific quantitative rules. Our premise here is that we can use cross-linguistic comparisons to determine which aspects of variation within a language are under language-specific control. This paper is intended as a first step in the direction of teasing apart the contributions of language-specific phonological contrasts, their phonetic implementations, and universal phonetic patterns to the observed acoustic structure of voiced and voiceless stops.

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Appendix. Positional allophones

Contrasting categories are separated by a dash. The transcriptions used are changed from the sources' somewhat for the sake of consistency, especially for the allophones. "Same" as an entry under medial or final allophones means same as material to the left, for the language, and not material above.

Language	Source(s)	Phonemes	Initial allophones	Medial allophones	Final allophones	Comments
Akan	Welmers (1946)	/p/–/b/	[pʰ] [pʲ]–[b] [bʲ]	Presumably same	None	Affrication, palatalization generally before /i/, /e/
		/t/–/d/	[tʰ] [ts]–[d] [dz]	Presumably same	None	
		/k/–/g/	[kʰ] [tʃ]–[g] [dʒ]	Presumably same	None	
		/kw/–/gw/	[kwʰ] [tʃwʲ]–[gw] [dʒwʲ]	Presumably same	None	
Alyawarra	Field notes, Nancy Turtle and Carol Morris	/p/	[p]	Same	None	Informal acoustic data, one speaker
		/t̪/	[t̪]	Same	None	
		/ṫ/	[ṫ]	Same	None	
		/ʈ/	[ʈ]	Same	None	
		/tj/ (alveopalatal)	[tʃ]	Same	None	
		/k/	[k]	Same	None	
Arabic (Egyptian)	Abdel-Massih (1975) Mitchell (1956)	/b/	[b]	Same	Same	[p] in loans only
		/t/–/d/	[t]–[d]	Same	Same	
		/ŧ/–/đ/	[ŧ]–[đ]	Same	Same	
		/k/–/g/	[k]–[g]	Same	Same	
		/ʔ/	[ʔ]	Same	Same	
Armenian (Eastern)	Allen (1950)	/pʰ/–/p'/–/b/	[pʰ]–[p']–[b]	[pʰ]–[p']–[b]	[pʰ]–[p'] [pʔ]–[b̥]	[b d g] after nasals
		/tʰ/–/t'/–/d/	[tʰ]–[t']–[d]	[tʰ]–[t']–[d]	[tʰ]–[t'] [tʔ]–[d̥]	Initial [b d g] followed by low pitched breathy V
		/kʰ/–/k'/–/g/	[k]–[k']–[g]	[kʰ]–[k']–[g]	[kʰ]–[k'] [kʔ]–[g̊]	Final /b d g/ are partly devoiced
		Also two affricate sets				
Basque	Azkue (1949) Tovar (1950)	/p/–/b/	[p]–[b]	Same	None	/p t k/ voiced after nasals
		/t/–/d/	[t]–[d]	Same	[t]	
		/k/–/g/	[k]–[g]	Same	[k]	
Bengali	Kostic *et al.* (1972) Dasgupta (1971)	/p/–/pʰ/–/b/–/bʱ/	[p]–[pʰ]–[b]–[bʱ] [ᵐbʱ]	Same	Same or [p]–[b]	
		/t̪/–/t̪ʰ/–/d̪/–/d̪ʱ/	[t̪]–[t̪ʰ]–[d̪]–[d̪ʱ] [ⁿd̪ʱ]	Same	Same or [t̪]–[d̪]	Also /t̪ː/, /d̪ː/
		/ʈ/–/ʈʰ/–/ɖ/–/ɖʱ/	[ʈ]–[ʈʰ]–[ɖ]–[ɖʱ] [ⁿɖʱ]	Same	None	
		/k/–/kʰ/–/g/–/gʱ/	[k]–[kʰ]–[g]–[gʱ] [ᵑgʱ]	Same	Same or [k]–[g]	Also /kː/, /gː/
Bobo	Morse (1980)	/p/–/b/	[pʰ]–[b]	[pʰ]–[b] [β]	None	Few borrowed geminates and clusters
		/t/–/d/	[tʰ]–[d]	Same	None	
		/k/–/g/	[kʰ]–[g]	Same	None	Palatals before [i], [ɪ]
Breton	Hardie (1948) Ternes (1970)	/p/–/b/	[pʰ]–[b]	Same	Same	Velars fronted before non-low V's
		/t̪/–/d̪/	[t̪ʰ]–[d̪]	Same	Same	Less aspiration before sonorants
		/c/–/ɟ/	[cʰ]–[ɟ]	Same	Same	Less aspiration after fricatives
		/k/–/g/	[kʰ]–[g]	Same	Same	No aspiration before fricatives
						Unreleased before obstruents
Bulgarian	Aronson (1968)	/p/–/b/	[p]–[b]	Same	[p]	Regressive voicing assimilation
		/t/–/d/	[t]–[d]	Same	[t]	Informal acoustic data for one speaker
		/k/–/g/	[k]–[g]	Same	[k]	
		Also palatalized stops				

... ison (1968)	/p/–/b/	[p]–[b]			... aspiration before fricatives
	/t/–/d/	[t]–[d]	Same	[p]	Unreleased before obstruents
	/k/–/g/	[k]–[g]	Same	[t]	Regressive voicing assimilation
	Also palatalized stops		Same	[k]	Informal acoustic data for one speaker

Appendix. (Continued)

Language	Source(s)	Phonemes	Initial allophones	Medial allophones	Final allophones	Comments
Burmese	Okell (1969)	/p/–/pʰ/–/b/	[p]–[pʰ]–[b]	[p][b]–[pʰ][b]–[b]	None	Dialects differ in medial voicing
		/t/–/tʰ/–/d/	[t]–[tʰ]–[d]	[t][d]–[tʰ][d]–[d]	None	
		/c/–/cʰ/–/ɟ/	[c]–[cʰ]–[ɟ]	[c][ɟ]–[cʰ][ɟ]–[ɟ]	None	Palatals may be affricates
		/k/–/kʰ/–/g/	[k]–[kʰ]–[g]	[k][g]–[kʰ][g]–[g]	None	
		/ʔ/	None	None	[p][t̪][t][c][k][ʔ]	Final /ʔ/ assimilates in phrases
Cantonese	Chao (1947) Kao (1971) Hashimoto (1972)	/p/–/pʰ/	[p]–[pʰ]	Same	[p°][pʔ]	Some tone co-occurrence restrictions
		/t/–/tʰ/	[t]–[tʰ]	Same	[t°][tʔ]	
		/k/–/kʰ/	[k]–[kʰ]	Same	[k°][kʔ]	
		/kw/–/kwʰ/	[kw]–[kwʰ]	Same	None	
Choctaw	Unpublished data, Linker	/p/–/b/	[pʰ][p]–[b][ɓ]	[pʰ][p]–[b]	[p°][p]	[b d g] before non-stress
		/t/	[tʰ][t]	[tʰ][t][d]	[t°][t]	Also medial geminates
		/k/	[kʰ][k]	[kʰ][k][g]	[k°][k]	Also [kʷ]
		/ʔ/	None	None	[ʔ]	
Cuna	Holmer (1947)	/p/–/pp/	[p][b]	[b]–[p:]	[p°]	
		/t/–/tt/	[t][d]	[d]–[t:]	[t°]	
		/k/–/kk/	[k][g̊]	[g]–[k:]	[k°]	
Danish	Fischer-Jørgensen (1954) Spore (1965)	/p/–/b/	[pʰ]–[b̥]	[pʰ][b]–[b][v]	[b]	Fischer-Jørgensen's acoustic data
		/t/–/d/	[tʰ]–[d̥]	[tʰ][d]–[d][ð]	[d][ð]	Final free variation in voicing
		/k/–/g/	[kʰ]–[g̊]	[kʰ][g]–[g][ɣ]	[g][ɣ]	
Dutch	Slatter (1961)	/p/–/b/	[p]–[b]	Same	[p]	Spirantization contrast before [ə]
		/t̪/–/d̪/	[t̪]–[d̪]	Same	[t̪]	
		/k/	[k]	Same	Same	
Efik	Ward (1933?)	/p/–/b/	[b]	[b][β]–[b]	[p]	
		/t/–/d/	[t]–[d]	[t][ɾ]–[ɾ]	[t°]	Medial [t] before stress only
		/k/	[k]	[k][ɣ]	[k]	Medial [k] before stress only
		/k͡p/	[k͡p]	Same	None	
English	Kahn (1976) Lisker & Abramson (1967)	/p/–/b/	[pʰ]–[b][b̥]	Same or [p]–[b]	[p][p°][pʔ]–[b][b̥][b°]	Medials "same" before stress
		/t/–/d/	[tʰ]–[d][d̥]	Same or [ɾ]	[t][t°][tʔ]–[d][d̥][d°]	
		/k/–/g/	[kʰ]–[g][g̊]	Same or [k]–[g]	[k][k°][kʔ]–[g][g̊][g°]	
Ewondo	Redden (1979)	/b/	[b]	[b][β]	[b̥]	Finals partly devoice
		/t/–/d/	[t]–[d]	[t]–[d][ɾ]	[d̥][ɾ]	
		/k/–/g/	[k]	[k]–[g][ɣ]	[g̊]	
		/k͡p/–/g͡b/	[k͡p]–[g͡b]	Same	None	
Finnish	Suomi (1980)	/p/	[p]	[p]	None	Also /p: t̪: k:/
		/t̪/–/d/	[t̪]	[t̪][d]	[t̪]	/d/ not underlying; some dialects [d̪][ɾ]
		/k/	[k]	[k]	None	
French	Armstrong (1978) Valdman (1976)	/p/–/b/	[p]–[b]	Same	Same	Finals always released
		/t̪/–/d̪/	[t̪]–[d̪]	Same	Same	Regressive voicing assimilation
		/k/–/g/	[k]–[g]	Same	Same	
Gaelic (Scots)	Borgstrøm (1937)	/p/–/b/	[pʰ]–[b̥][ᵐb]	[p]–[mb]	[p°]	
		/t̪/–/d̪/	[t̪ʰ]–[d̪][ⁿd]	[t̪]–[nd]	[t°]	Also palatalization
		/k/–/g/	[kʰ]–[g̊][ᵑg]	[k]–[ŋg]	[k°]	Some voicing of /p t k/ after nasals
		Also preaspirated stops				

Appendix. (Continued)

Language	Source(s)	Phonemes	Initial allophones	Medial allophones	Final allophones	Comments
German	Moulton (1962)	/p/–/b/	[pʰ]–[b̥]	[pʰ][p]–[b]	[pʰ]	Deaspiration variable before
	Korlén (1979)	/t/–/d/	[tʰ]–[d̥]	[tʰ][t]–[d]	[tʰ]	nonstress
		/k/–/g/	[kʰ]–[g̊]	[kʰ][k]–[g]	[kʰ]	
Hausa	Kraft & Kraft (1973)	/b/–/ɓ/	[b][p][pʰ][w][f]–[ɓ][b̰]	Same	None	Medials less voiced than initials
	Meyers (1976)	/t/–/d̥/–/ɗ/	[tʰ]–[d̥][d]–[ɗ][d̰]	Same	None	Glottalization decreases voicing
		/k/–/k'/–/g/	[kʰ]–[k']–[g][g̰]	Same	None	Also palatalized, labialized allophones of velars
		/ʔ/	[ʔ]	Same	None	
Hawaiian	Pukui & Elbert (1965)	/p/	[p]	Same	None	Informal acoustic data, 1 speaker
		/k/	[k][t]	Same	None	
Hindi-Urdu	Kostić *et al.* (1975)	/p/–/b/–/pʰ/–/bʱ/	[p]–[b]–[pʰ]–[b̤ʱ]	Same	[p]–[b][p]–[p][Φ]–[b̤ʱ]	Deaspiration before non-stress
	Arun (1961)	/t̪/–/d̪/–/t̪ʰ/–/d̪ʱ/	[t̪]–[d̪]–[t̪ʰ]–[d̪ʱ]	Same	[t̪]–[d̪][t̪]–[t̪]–[d̪ʱ]	Final /b d̪/ if not devoiced may be slightly implosive or unreleased
		/ʈ/–/ɖ/–/ʈʰ/–/ɖʱ/	[ʈ]–[ɖ]–[ʈʰ]–[ɖʱ]	Same	[ʈ]–[ɽ]–[ʈ]–[ɽʱ]	
		/k/–/g/–/kʰ/–/gʱ/	[k]–[g]–[kʰ]–[gʱ]	Same	[k]–[g]–[k]–[gʱ]	
		/q/ (from Urdu)	[q]	Same	Same	
		Also affricate series				
Hungarian	Kálmán (1972)	/p/–/b/	[p]–[b]	Same	Same	Also affricate series,
		/t̪/–/d̪/	[t̪]–[d̪]	Same	Same	including palatals
		/k/–/g/	[k]–[g]	Same	Same	
Japanese	Daniels (1958)	/p/–/b/	[p][pʰ]–[b][b̥]	Same	None	Sources disagree on extent of
	Han (1962)	/t̪/–/d̪/	[t̪][t̪ʰ]–[d̪][d̪̥]	Same	None	aspiration
		/k/–/g/	[k][kʰ]–[g][g̊]	Same	None	
Kaititj	Field notes, Harold Koch	/p/	[p]	Same	None	Also labialized stops
		/t̪/	[t̪]	Same	None	
		/t/	[t]	Same	None	
		/ʈ/	[ʈ]	Same	None	
		/tj/ (lamino-palatal)	[cç]	Same	None	
		/k/	[k]	Same	None	
		Also prenasalized stops				
Kikuyu	Armstrong (1940)	/ᵐb/	[ᵐb]	Same	None	
		/t/–/ⁿd/	[t]–[ⁿd]	Same	None	
		/c/–/ᶮj/	[tʃ]–[ⁿdʒ]	Same	None	
		/k/–/ᵑg/	[k]–[ᵑg]	Same	None	
Kirghiz	Hebert & Poppe (1963)	/p/–/b/	[pʰ]–[b̥]	[p]–[b]	[p]–[b̥][b]	Final devoicing after V: or heavy stress
		/t̪/–/d̪/	[t̪ʰ]–[d̪̥]	[t̪]–[d̪]	[t̪]–[d̪̥][d̪]	
		/q/–/G/	[kʰ][qʰ]–[g][G̥]	[k][q]–[g][G]	[k][q]–[g̊][g][G̥][G]	Also palatalized allophones
Korean	Martin & Lee (1969)	/p/–/pʰ/–/P/	[p]–[pʰ]–[P]	[b]–[pʰ]–[P]	[p˺]	[p] slightly aspirated, [pʰ] heavily
		/t/–/tʰ/–/T/	[t]–[tʰ]–[T]	[d]–[tʰ]–[T]	[t˺]	[P] unaspirated, "tense"; similarly, other places of artic.
		/k/–/kʰ/–/K/	[k]–[kʰ]–[K]	[g]–[kʰ]–[K]	[k˺]	[b d g] also after nasals, laterals
Mandarin	Chao (1968)	/p/–/pʰ/	[p]–[pʰ]	Same or [b]–[p]	None	Medial voicing and deaspiration in
	Dow (1972)	/t/–/tʰ/	[t]–[tʰ]	Same or [d]–[t]	None	toneless syllables
		/k/–/kʰ/	[k]–[kʰ]	Same or [g]–[k]	None	
		Also 3 affricate sets				

Appendix. (Continued)

Language	Source(s)	Phonemes	Initial allophones	Medial allophones	Final allophones	Comments
Marathi	Jha (1977)	/p/–/pʰ/	[p]–[pʰ]	Same	Same	
		/t̪/–/t̪ʰ/–/d̪/–/d̪ʱ/	[t̪]–[t̪ʰ]–[d̪]–[d̪ʱ]	Same	Same	
		/ʈ/–/ʈʰ/–/ɖ/–/ɖʱ/	[ʈ]–[ʈʰ]–[ɖ]–[ɖʱ]	[ʈ]–[ʈʰ]–[ɽʰ]	[ʈ]–[ʈʰ]–[ɽʰ]	
		/k/–/kʰ/–/g/–/gʱ/	[k]–[kʰ]–[g]–[gʱ]	Same	Same	
		Also dental and palatal affricates				
Nama	Beach (1938)	/p/	[p]	[p]	[p˺]	
		/t̪/	[t̪]	None	None	/t/, /k/ voiced after rising tone
		/k/	[k] [c]	None	None	[c] before front vowels
Norwegian	Vanvik (1972)	/p/–/b/	[pʰ]–[b]	[pʰ] [p]–[b]	[p]–[b]	Informal acoustic data, 1 speaker
		/t̪/–/d̪/	[t̪ʰ]–[d̪]	[t̪ʰ] [t̪]–[d̪]	[t̪]–[d̪]	Deaspiration before non-stress but overall variation unclear
		/ʈ/–/ɖ/	None	[ʈʰ] [ʈ]–[ɖ]	[ʈ]–[ɖ]	
		/k/–/g/	[kʰ]–[g]	[kʰ] [k]–[g]	[k]–[g]	
Persian	Obolensky *et al.* (1963)	/p/–/b/	[pʰ]–[b̥] [b]	Same	Same	Variation somewhat unclear
		/t̪/–/d̪/	[t̪ʰ]–[d̪̥] [d̪]	Same	Same	Also /d:/
		/k/–/g/	[kʰ]–[g̊] [g]	Same	Same	
		/G/	[q] [G]	[q] [G] [ɣ]	Same	
Polish	Vihoś (1977)	/p/–/b/	[p] [pʰ]–[b]	Same	[p] [b̥]	
		/t̪/–/d̪/	[t̪] [t̪ʰ]–[d̪]	Same	[t̪] [d̪̥]	
		/k/–/g/	[k] [kʰ]–[g]	Same	[k] [g̊]	
		Also palatalized stops				
Russian	Jones & Ward (1969)	/p/–/b/	[p]–[b]	Same	[p]	
		/t̪/–/d̪/	[t̪]–[d̪]	Same	[t]	
		/k/–/g/	[k]–[g]	Same	[k]	
		Also palatalized stops				
Spanish	Harris (1969)	/p/–/b/	[p]–[b]	[p]–[β]	[β]	
		/t̪/–/d̪/	[t̪]–[d]	[t]–[ð]	[ð]	
		/k/–/g/	[k]–[g]	[k]–[ɣ]	[ɣ]	
Swahili	Polomé (1967)	/p/–/pʰ/–/ɓ/	[p]–[pʰ]–[ɓ]	Same	Rare	Stops not implosives after nasals
		/t/–/tʰ/–/ɗ/	[t]–[tʰ]–[ɗ]	Same	Rare	Fewer aspirates medially before unstressed V's
		/c/–/cʰ/–/ʄ/	[t]–[tʃʰ]–[dʒ]	Same	Rare	
		/k/–/kʰ/–/ɠ/	[k]–[kʰ]–[ɠ]	Same	Rare	Velars backed before back V's
Swedish	Lundström & af Trampe (1977)	/p/–/b/	[pʰ]–[b]	[pʰ] [p]–[b]	[pʰ]–[b]	Also germinates
		/t̪/–/d̪/	[t̪ʰ]–[d̪]	[t̪ʰ] [t̪]–[d̪]	[t̪ʰ]–[d̪]	Deaspiration before non-stress
		/ʈ/–/ɖ/	None	[ʈʰ] [ʈ]–[ɖ]	[ʈʰ]–[ɖ]	
		/k/–/g/	[kʰ]–[g]	[kʰ] [k]–[g]	[kʰ]–[g]	
Tagalog	Schachter & Otanes (1972)	/p/–/b/	[p]–[b]	Same	[p°]–[b°]	Informal acoustic data, 1 speaker
		/t̪/–/d̪/	[t̪]–[d]	Same	[t°]–[d°]	
		/k/–/g/	[k]–[g]	Same	[k°]–[g°]	
Tamil	Personal communication, Sarah Dart, UCLA	/p/–/pp/	[p]	[b] [β]–[p:]	None	Slight aspiration before back vowels
		/t̪/–/t̪t̪/	[t̪]	[d̪] [ð]–[t̪:]	None	
		/ʈ/–/ʈʈ/	None	[ɖ]–[ʈ:]	None	
		/k/–/kk/	[k]	[g] [ɣ]–[k:]	None	

Appendix. (Continued)

Language	Source(s)	Phonemes	Initial allophones	Medial allophones	Final allophones	Comments
Thai	Haas (1955)	/p/–/pʰ/–/b/	[p]–[pʰ]–[b]	Presumably same	[b̥°]	
		/t/–/tʰ/–/d/	[t]–[tʰ]–[d]	Presumably same	[d̥°]	
		/c/–/cʰ/	[c]–[cʰ]	Presumably same	None	
		/k/–/kʰ/	[k]–[kʰ]	Presumably same	[g̊°]	
		/ʔ/	[ʔ]	Same	Same	
Tikar	Personal communication, Ellen Jackson, UCLA	/p/–/b/–/ɓ/	[p]–[b]–[ɓ]	[p]–[mb] [β]–[ɓ] [β]	[β̊] [b̥°]	
		/t/–/d/–/ɗ/	[t]–[d]–[ɗ]	[t]–[nd] –[ɗ]	None	
		/k/–/ɠ/	[k] ---- [ɠ]	[k] –[ɠ]	None	
Tiwi	Osborne (1974)	/p/	[p] [b̥] [pʰ]	Same	None	
		/t̪/	[t̪] [d̪] [t̪ʰ]	Same	None	No intervocalic voicing
		/t/	[t] [d̥] [tʰ]	Same	None	
		/k/	[k] [g̊] [kʰ]	Same	None	
Tswana	Cole (1955)	/p'/–/pʰ/–/b/	[p'] [p]–[pʰ]–[b] [β]	Same	None	Labialization before back vowels
		/t'/–/tʰ/	[t'] [t]–[tʰ]	Same	None	[cʰ] before [i],
		/k'/–/kʰ/	[k'] [k] [c]–[kˣ] [kʰ] [cʰ]	Same	None	[c] before front V's,
		/tl'/–/tlʰ/	[tl'] [tl]–[tlʰ]	Same	None	[kˣ] before [-high] V's
Tzeltal	Kaufman (1971)	/p/–/p'/–/b/	[p]–[p']–[b]	[p]–[p']–[β]	[pʰ]–[p']–[β̊]	
		/t̪/–/t̪'/–/d/	[t̪]–[t̪']–[d̪]	[t̪]–[t̪']–[ð]	[t̪ʰ]–[t̪']–[ð̊]	/d̪/, /g/ in Spanish loans only
		/k/–/k'/–/g/	[k̟]–[k̟']–[g]	[k̟]–[k̟']–[ɣ]	[k̟ʰ]–[k̟']–[ɣ̊]	Finals may have voiceless V
Vietnamese	Thompson (1965)	/b/	[b] [ɓ]	Presumably same	[p°]	
		/t/–/tʰ/–/d/	[t]–[tʰ]–[d] [d]	Presumably same	[t°]	Also final [k͡p°]
		/ʈ/	[ʈ]	Presumably same	None	
		/c/	[c]	Presumably same	[c°]	
		/k/	[k]	Presumably same	[k°]	
Yidiɲ	Dixon (1977)	/b/	[b] [b̥]	[b]	None	/ɣ/ has [g] after nasals
		/d/	[d] [d̥]	[d]	None	
		/dɟ/ (alv. + pal.)	[dɟ] [d̥ɟ̊]	[dɟ]	None	
		/g/	[g] [g̊]	[g]	None	
Zoque	Wonderly (1951)	/p/–/b/	[p]–[b]	[p]–[β]	[pʰ]	
		/t/–/d/	[t]–[d]	[t]–[ð]	[tʰ]	Degree of aspiration varies with position
		/tʲ/–/dʲ/	[tʲ]–[dʲ]	[tʲ]	None	
		/c/–/ɟ/	[tʃ]–[ndʒ]	[tʃ]	[tʃʰ]	
		/k/–/g/	[k]–[g]	[k]–[ɣ]	[kʰ]	