The phantom in the phoneme: Invariant cues for stop consonants*

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The stop consonants /b, d, g, p, t, k/ were recorded before /i/, /a/, /u/. The energy spectrum for each stop consonant was removed from its original vowel and spliced onto a different steady-state vowel. Results of a recognition test revealed that consonants were accurately recognized in all cases except when /k/ or /g/ was spliced from /i/ to /u/. Further demonstrations suggested that /k/ and /g/ do have invariant characteristics before /i/, /a/, and /u/. These results support the general notion that stop consonants may be recognized before different vowels in normal speech in terms of invariant acoustic features.

The simplest view of speech perception states that each phoneme in a language is accompanied by a unique combination of acoustic features; whenever a particular phoneme occurs in speech, these features also occur. According to this view, speech perception need only involve, at the simplest level of analysis, the identification of particular configurations of acoustic features.

In fact, a number of consonant phonemes in English are accompanied by invariant acoustic features. The noise which accompanies /s/, /z/, /sh/, /ch/, /j/, and /zh/ provides sufficient information for listeners to discriminate these phonemes in any syllable environment (Harris, 1958; Heinz & Stevens, 1961). Moreover, it is possible to demonstrate the featural composition of these consonants. For example, /s/-/z/ differ mainly in terms of voicing; /z/ is accompanied by low-frequency vowel resonance, while /s/ is not. When /z/ is passed through a filter which eliminates energy below 800 Hz, listeners hear /s/. The consonants /sh/, /ch/, /j/, and /d/ differ mainly in terms of their duration. This is demonstrated by splicing successive 10-msec segments from the onset of /sha/, in which case listeners eventually hear /cha/, then /ja/, and then /da/ (Scott, 1971).

Other sounds, such as the consonants /f/-/θ/, /v/-/ð/, and /m/-/n/ require the identification of both invariant and variant cues for their perception (Harris, 1958; Malecot, 1956). As shown in Fig. 1, the two phonemes in each pair share invariant cues that allow listeners to discriminate these consonants from all others in English. For example, /f/ and /θ/ contain low-intensity high-frequency energy, /v/ and /ð/ are accompanied by this same energy plus a low-frequency voicing component, while /m/ and /n/ are accompanied by nasal resonance and a complete lack of high-frequency energy. Thus, the two consonant phonemes in each row in Fig. 1 share invariant cues. In order for listeners to discriminate

between the two members of each pair, information is needed from the vowel portion of the syllable. The first member of each pair is articulated toward the front of the mouth and is accompanied by a rising frequency transition to the following vowel, while the second consonant in each pair is articulated at the center of the

Fig. 1. Speech spectrograms of pairs of sounds illustrating the complex relationship between invariant and transitional cues. The two syllables in each row share invariant cues that distinguish the two consonant phonemes from all others in English. The two syllables in each row differ by place of articulation, which is cued by the slope of the second (upper) formant transition (F2). In syllables on the left of the figure, F2 is rising, in syllables on the right, F2 is falling.

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mouth and is accompanied by a falling frequency transition. Thus, perception of these consonants requires simultaneous identification of invariant and transitional cues.

The view of distinctive features as patterns of invariant acoustic energy appears to break down when one considers the stop consonants. These consonants (/b, d, g, p, t, k/) carry the highest information load of any class of phonemes in English. The difficulty is that the cues which signal the stop consonants seem to change, depending upon the vowel context in which the consonant occurs. For this reason, various investigators (e.g., Stevens & Halle, 1964, p. 90) argue that phonemes may be adequately described as sets of distinctive features, but these features cannot be identified in the speech wave.

In normal speech, a stop consonant is preceded by silence and is accompanied by an explosive burst of energy when the consonant is released, followed by a period of aspiration which is longer for the unvoiced stops /p, t, k/ than for the voiced stops /b, d, g/. When producing a voiced stop, the speaker may initiate voicing while his oral cavity is still gliding from the position assumed for the consonant to the position assumed for the vowel. When this gliding movement is accompanied by vocalization, the result is a rapid frequency change at the beginning of the vowel. These "vowel transitions" have been shown to be sufficient cues for the perception of the voiced stops, and these transitions differ for a particular consonant in different vowel environments (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). For the unvoiced stops, the consonant is followed by steady-state vowel formants, although frequency transitions may be observed in the aspirated portion of the sound, especially for /k/.

Several investigators have examined the role of the stop burst in the perception of unvoiced stops. Halle, Hughes, and Radley (1957) gated out the bursts for /p/, /t/, /k/ occurring at the end of a word and randomly presented these isolated bursts to listeners for recognition. This task was found to be very difficult for Ss because of the extremely short burst duration of unvoiced stops in final position. However, with practice, the five best Ss correctly recognized 65%, 70%, 75%, 80%, and 96% of the bursts.

Liberman, Delattre, and Cooper (1952) used a pattern playback machine to present artificial bursts at specific frequencies before synthetically produced vowels. The synthetically produced "teardrop shaped" bursts were all 15 msec in duration and were presented as 12 different frequencies at 360-Hz intervals before the vowels /i, e, ε, ɔ, o, u/. Listeners were told to report whether they heard /p/, /t/, or /k/ before each vowel. The results showed that burst frequencies above 3,240 Hz were heard as /t/ before all vowels. A burst presented at 360 Hz was always heard as /p/. In addition, bursts between 1,080 and 2,160 Hz were heard as /p/ before /i, e, o, u/ but not before /ε, a, ɔ/. Bursts at

720 and 1,080 Hz were heard as /k/ in front of all vowels except /i/ (no single frequency was found to produce /k/ before /i/). In addition, bursts presented at the frequency of the second formant of the following vowel were heard as /k/. In their discussion of the results, Liberman et al chose to emphasize the *variability* of the data for /p/ and /k/, and concluded that "the results of this experiment show clearly the influence of the following vowel on the perception of the schematic stops /p/ and /k/ [p. 512]." However, it seems to us that the most significant result of the Liberman et al study is that there does exist a single burst frequency for each of the unvoiced stops which serves as a cue for that consonant (the single exception being /k/ before /i/, for which no burst frequency was identified).

The role of vowel context in the perception of the unvoiced stop /k/ was investigated by Schatz (1954). Schatz removed the initial 20-msec explosive burst from /ki/, /ka/, /ku/ and spliced the burst from each of these syllables onto /hi/, /ha/, and /hu/. Since /k/ in initial position in a syllable consists of an explosive burst of 5-10 msec followed by aspiration for a slightly longer period (30-60 msec) prior to the vowel, the syllables /hi/, /ha/, /hu/ were used to create the impression of aspiration. For each of these syllables, the /h/ was shortened to 60 msec. When the burst from /ki/ was spliced before /hi/, /ha/, /hu/, Ss heard /ki/, /ta/, /pu/; the burst from /ka/ yielded /pi/, /ka/, /pu/ and the burst from /ku/ yielded /pi/ or /ki/, /pa/, /ku/. Thus, when the original 20-msec burst from /k/ was spliced onto the same vowel (preceded by aspiration) from which it had been removed, Ss always heard /k/. However, when the vowel context was changed, perception of the consonant sound was altered. These results for /k/ agree almost perfectly with the results obtained by Liberman et al for /k/ using synthetic speech.

The experiments by Liberman et al and Schatz demonstrate that a single cue, burst frequency, does not provide sufficient information to identify /k/ in all syllable environments. However, the stimuli presented to Ss in these experiments do not contain the same information that accompanies stop consonants in normal speech. For example, using aspirated portions of exactly 60 msec eliminates duration of the consonant as a cue to its identity and distorts the shape of the envelope. Fischer-Jorgensen (1954), for example, found that in 1,368 spectrograms, the duration of aspiration following the burst was always longer for /g/ than for either /b/ or /d/.

Harris (1953) used tape splicing to transpose the *entire* energy spectrum of a consonant phoneme from one syllable to another. Harris identified the initial consonant portion of a CVC syllable by manually drawing recording tape over the playback head of a tape recorder and listening for the onset of the consonant and the onset of vowel resonance. The entire energy spectrum for the initial consonant was then removed from its original syllable and spliced onto a new VC

syllable from which the original consonant had previously been removed. Harris used 20 different consonants, which were transposed between six different vowel environments /I/-/I/; /u/-/I/; /ɔ/-/æ/; /i/-/æ/; /eI/-/o/; /a/-/o/. In each case, the 20 consonants were transposed from the first vowel to the second. Results of the listening test revealed that syllables were identified with an overall accuracy of slightly better than 80% (chance equals 5%). The results for the six stop consonants (summed over the different vowel conditions) were: /b/ 87%, /d/ 78%, /g/ 78%, /p/ 33%, /t/ 95%, /k/ 80%. It is clear that the energy spectrum which accompanies a stop consonant contains invariant information over a wide range of vowel environments. In the Harris experiment, only /p/ was identified with less than 75% accuracy when it was transposed from one syllable to another. When /p/ was misperceived, it was consistently heard as /t/.

The scores on the listening test might have improved if Harris had removed formant transitions from the vowels prior to splicing a consonant from one vowel environment to another. Since vowel formants change, depending upon the place of articulation of the preceding vowel, transposed syllables often had formant transitions that were inappropriate to the syllable. For example, in one condition, the syllable /gok/ was formed by splicing /g/ from /ga/ onto /ok/ removed from /mok/. Since /m/ is articulated in the front of the mouth, the vowel transitions before /o/ are quite different from those which would normally accompany /gok/. Thus, S may have had difficulty integrating the /g/ in /gok/ with the vowel /o/ because of the abnormal vowel transitions.

The present research systematically investigates the amount of perceptual invariance for stop consonants, using the tape splicing technique originally employed by Harris (1953). Experiment I examines the amount of invariant information by transposing consonants between the steady-state vowels /i/ and /u/. These two vowels have the most disparate energy spectra of any two vowels in English. If, for example, the energy spectrum for /d/ contains invariant information, it should be possible to transpose the consonant energy between /di/ and /du/ (after removing vowel transitions) without altering perception of the original syllables. Experiment II extends the results of Experiment I to the middle vowel /a/ for the unvoiced stops /p/, /t/, /k/.

EXPERIMENT I

Method

Subjects

Forty-two students from the University of Waterloo served as Ss. Each S was tested individually in a small sound-attenuated room with E, in a session lasting about 30 min.

Stimuli

Each of the six stop consonants was spoken 40 times before

/i/ and before /u/, producing a total of 480 stimuli. From these original stimuli two types of syllables were constructed: (a) syllables in which transitions were removed, and the initial stop burst plus aspiration was spliced back onto the steady-state vowel, and (b) syllables in which the consonant (burst plus aspiration) originally taken from /i/ was spliced onto /u/, or vice versa. Stimulus tapes were constructed by first recording all 480 syllables in a randomly determined order. Then the initial consonant energy was removed from each syllable, using the following values (in milliseconds): /b/ 20, /d/ 30, /g/ 40, /p/ 60, /t/ 80, /k/ 100. These values were arrived at by inspection of speech spectrograms of the stimuli. The onset of each consonant was determined by manually drawing the recording tape over the playback head of the tape recorder, and monitoring the output via earphones and a Tektronix oscilloscope.

All 480 consonants excised from the vowel were played in isolation. By listening to these sounds (burst plus aspiration), we were able to ascertain that consonants were not followed by vowel resonance. For the voiced stops /b/, /d/, /g/, the energy accompanying the consonant is quite short, and it is difficult to discriminate one voiced stop from another. However, the unvoiced stops /p/, /t/, /k/ were readily identifiable by both authors when the consonant energy was removed from the vowel.

After removing the burst and aspiration portion of each CV syllable according to the above values, the next 50 msec was excised from the remaining vowel portion of the syllable to insure that a steady-state vowel remained. Then all 480 vowels were played to insure that a pure vowel sound was heard and not a stop consonant cued by formant transitions. On those cases where /b/ was heard (due to the abrupt onset caused by tape splicing), additional 10-msec segments were removed until a pure vowel was heard. Thus, perceptual criteria were used to insure that the noise portion of the stop consonant was paired with a steady-state vowel.

For half of the syllables, the consonant was spliced back onto the original vowel to produce transitionless syllables. For the remaining one-half of the syllables, the consonant was transposed between /i/ and /u/. Energy was always transposed between vowels originally having the same consonant, such as /bi/ and /bu/. Examples of original and transposed syllables are shown for each stop consonant in Figs. 2 and 3.

Procedure

The stimulus tape was presented on a Sony Model TC630 tape recorder connected to a Dynaco loudspeaker by means of a Dynaco amplifier and preamplifier. S was seated in front of the loudspeaker in a sound-attenuated room. Stimuli were presented at the rate of one every 4 sec. After each presentation, S was instructed to write one of the 12 possible syllables on his answer sheet. S was instructed to guess if he was uncertain of the sound.

Results

The results of the listening test are shown in Table 1.¹ Inspection of this table reveals a high degree of perceptual invariance for stop consonants. Performance was essentially perfect for sounds with vowel transitions removed. For the transposed syllables, Ss consistently identified syllables in which the initial segment was transposed from /u/ to /i/. When the initial segment was transposed from /i/ to /u/, Ss accurately identified bilabial and alveolar stops, but fell to 54% accuracy for /kju/ (/k/ from /ki/ spliced onto /u/), and were completely at chance for /giu/ (/g/ from /gi/ spliced onto /u/). An examination of intrusion errors revealed that

Fig. 2. Speech spectrograms of voiced stops used in this experiment before /i/ and /u/. The stimuli in the top row consist of syllables in which vowel transitions were excised from the syllable, and the stop burst and aspiration were spliced onto the remaining steady-state vowel. Note the absence of transitions at the onset of the vowel as compared to the vowels in Fig. 1. The syllables in the lower panel are examples of stimuli in which the stop burst and aspiration for each voiced stop were transposed between /i/ and /u/.

Fig. 3. Speech spectrograms of control syllables (upper panel) and transposed syllables (lower panel) for the unvoiced stops.

/kju/ was identified as /pu/ 63% of the time and as /tu/ 27%, while /giu/ was perceived as /bu/ 90% of the time and as /du/ 9%.

The relatively poor results for /kju/ and /giu/ may not reflect a lack of *acoustic* invariance for the velar consonants. When /k/ and /g/ are spoken before /i/, they are accompanied by energy in the region of the second vowel formant (about 3,000 Hz), which is not present when /k/ and /g/ are spoken before /u/. This is due to the fact that /k/ and /g/ are produced with a closure nearer to the front of the mouth for /i/. This frequency component at 3,000 Hz is not a necessary cue for the perception of /k/ or /g/, since Ss had no difficulty identifying syllables in which the initial energy for /ku/ or /gu/ was spliced onto /i/. It is only when the stop burst from /k/ or /g/ is transposed from /i/ to /u/ that Ss had difficulty identifying the sounds. This suggests that the energy at 3,000 Hz which accompanies /kju/ and /giu/ caused Ss to misperceive these syllables, probably because /ku/ and /gu/ are never accompanied by high-frequency energy in normal speech.

To test this hypothesis, all of the transposed syllables were passed through a filter which eliminated energy above 2,000 Hz. While filtering had little effect upon the perception of any of the other transposed syllables, Ss correctly identified /kju/ and /giu/.

In a second demonstration, the consonant portion from /gi/ or /ki/ was substituted with the consonant portion from /gu/ or /ku/, respectively, in normal speech. For this experiment, we recorded 10 short phrases such as "the sterile cuckoo" or "Hungarian goulash," and replaced the initial stop in /kuku/ and /gulaš/ with the appropriate consonant removed from /gi/ or /ki/. For all of these altered phrases, listeners heard a perfectly clear /g/ or /k/ at the beginning of the word. The high-frequency energy which accompanies the consonant from /ki/ and /gi/ was typically heard as a click or as background noise.

In a final demonstration, tape loops were made of each of the transposed stimuli, and five Ss were randomly presented with each of these syllables at the rate of 2/sec for 1 min. When /kju/ and /giu/ were presented, all Ss reported hearing /ku/ and /gu/ after three or four repetitions. Repetition of these syllables caused Ss to regard the high-frequency component of /kju/ and /giu/ as irrelevant information which was heard as nonspeechlike background noise. None of the other transposed syllables were heard to change in this way, although several Ss reported hearing complete satiation of the consonant portion of the syllable. This later finding is discussed more fully by Scott and Cole (1972).

EXPERIMENT II

Experiment II was performed in order to extend the results of Experiment I to syllables produced before the midvowel /a/.

Table 1
Percent Correct Recognition Scores

Control						
	/b/	/d/	/g/	/p/	/t/	/k/
/i/	99	100	98	100	99	99
/u/	100	100	100	99	99	99
Transposed						
	/b _u i/	/d _u i/	/g _u i/	/p _u i/	/t _u i/	/k _u i/
	96	92	82	98	97	98
	/b _i u/	/d _i u/	/g _i u/	/p _i u/	/t _i u/	/k _i u/
	94	99	21	98	89	54

Method

Subjects

Ten students from the University of Waterloo served as Ss. Each S was tested in a small room with E in a session lasting approximately 30 min.

Stimuli

The syllables /pi/, /pu/, /ti/, /tu/, /ki/, /ku/ were recorded 10 times each, while /pa/, /ta/, /ka/ were recorded 20 times each in random order on magnetic tape. Following the identical procedures used in Experiment I, the consonant portion of the energy spectrum was transposed between /i/ and /a/ and between /u/ and /a/ for each of the unvoiced stops. Thus, Ss heard 120 syllables in random order, 10 each of /p_ia/, /p_ai/, /p_ua/, /p_au/, /t_ia/, /t_ai/, /t_ua/, /t_au/, /k_ia/, /k_ai/, /k_ua/, /k_au/.

Procedure

S was seated in front of a Dynaco loudspeaker and was presented the 120 syllables at the rate of 1 every 4 sec. S was instructed that on each trial he would hear /p/, /t/, or /k/ paired with /i/, /a/, or /u/. S was instructed to write /p/, /t/, or /k/ on his answer sheet after hearing a sound, and to guess if he was uncertain of a particular sound.

Results

The results of the listening test are presented in Table 2. It can be seen that scores were uniformly high for all of the transposed syllables. Overall, Ss identified unvoiced stops transposed between /i/-/a/ with 89% accuracy and between /u/-/a/ with 91% accuracy (chance = 33%). It is interesting that performance was quite high for /k_aa/ (78%) since performance was relatively low for /k_iu/ in Experiment I. This suggests that the low scores for /k_iu/ may represent a single case when invariance breaks down for the unvoiced stops.

DISCUSSION

This research demonstrates that the energy spectrum which accompanies the noise portion of a stop consonant in initial position contains invariant perceptual information for /b/, /d/, /p/, and /t/. In addition, a number of demonstrations suggest that /g/ and /k/ also have an underlying acoustic invariance. Our data, considered together with the results of Harris

Table 2
Percent Accuracy Identification Scores for /p/, /t/, /k/
Transposed Between /i/-/a/ and /u/-/a/

/p _u a/ 83	/p _a u/ 99	/p _i a/ 94	/p _a i/ 99
/t _u a/ 93	/t _a u/ 100	/t _i a/ 98	/t _a i/ 88
/k _u a/ 100	/k _a u/ 70	/k _i a/ 78	/k _a i/ 75

(1953), show that listeners can accurately identify certain stop consonants that have been transposed from one vowel environment to another.

It is possible that the noise portions of the stop consonants that were transposed from one syllable to another did contain some frequency transitions embedded within the noise (although these were not evident in speech spectrograms). For example, in some cases, the noise burst is continuous with the onset of the vowel transition, and in these cases it is difficult to isolate a "pure" burst for the stop consonant. However, the presence of these transitions should not have aided in perception of the stop consonant in transposed syllables, since these transitions by themselves are not commutable elements (Liberman et al, 1967, p. 436). The essential point demonstrated in this experiment is that the entire energy spectrum that accompanies a stop consonant prior to the vowel transitions contains invariant perceptual information.

A recent experiment by Winitz, Scheib, and Reeds (1972) strongly supports our results for the unvoiced stops /p, t, k/. These authors removed the acoustic energy that accompanies /p, t, k/ from conversational speech and presented the isolated segments to listeners for identification. All consonants were identified accurately when they were removed from initial or final position in a word before or after /i, a, u/. The only exception was /k/ before /i/, which was often misperceived. These findings are in perfect agreement with the results of the present experiment.

Examination of speech spectrograms (see Figs. 2 and 3) reveals that the overall energy spectrum for a given stop consonant does change from one vowel environment to another. In particular, the aspirated portion of /p/ and /k/ following the stop burst is accompanied by concentrations of energy in the region of the second formant of the following vowel. This frequency information is not an essential cue for perception of /p/ or /k/ since it may be removed by filtering without altering perception of the consonant. However, this frequency information can interfere with perception of /k/ when it is transposed from /i/ to /u/.

Thus, a stop consonant is composed of invariant features as well as features which vary from one vowel environment to another. For /t/, the invariant feature consists of high-frequency noise. But what are the invariant characteristics of /p/ and /k/? Recent research in our laboratory has shown that the shape of the

envelope that accompanies /p/ and /k/ may contain invariant information for identifying these consonants (Scott, 1973).

The majority of research in speech perception has involved synthetic stimuli and has focused on isolated cues such as stop bursts or vowel transitions. The conclusion of much of the research with synthetic speech is that the acoustic information needed to identify the stop consonants is embedded in the vowel portion of a consonant-vowel syllable, so that consonants must be recoded from the energy in the speech wave before they are identified (Liberman et al, 1967). In fact, Liberman (1970) maintains that there is a grammar of consonants and vowels no different in principle from the grammar which speakers use to generate and understand sentences.

The present research demonstrates a high degree of acoustic invariance for the most problematic phonemes in the English language, the stop consonants. The stop consonants in initial position consist of both invariant cues and transitional cues which vary from one vowel environment to another. The literature on speech perception has shown that the perceptual system can and does make use of both types of cues; however, the overwhelming emphasis has been placed on the variable transitional cues. It is highly unlikely that a process as evolutionarily advanced as speech perception would fail to utilize all of the available information contained in the speech wave. It is our belief that the process of speech perception is not confined to the analysis of primarily one type of cue, but rather an analysis of all the available cues.

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NOTE

1. The data for /g/ and /k/ are based on the listening scores of the second 21 Ss only. Scores for the first 21 Ss were not considered for the velars because it was discovered that a 30-msec burst had been used instead of a 40-msec burst. An analysis of variance revealed no difference in listening scores for the first or second group of Ss for any of the other phonemes.

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