Adaptive estimation of phoneme boundaries and selective adaptation for speech

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Previous studies have estimated the boundary between two phoneme categories from identification data. This procedure is time consuming, especially in studies of selective adaptation, in which it is necessary to test identification twice, before and during adaptation. We adapted a simple up-down adaptive procedure to estimate the phoneme boundary. The stimulus to be presented on a given trial is determined from the subjects' past responses. Two stimulus continua were synthesized: a voicing continuum (13 stimuli changing from /ba/ to /pa/) and a place continuum (13 stimuli changing from /ba/ to /da/ and /ga/). Twenty-two normal listeners were given an identification test with each set of stimuli. A logistic curve was fit to the obtained identification function from each subject. Next, phoneme boundaries were directly estimated with the adaptive procedure. The 50% points on the curves from the identification procedure were highly correlated with those estimated by the adaptive procedure. Phoneme boundaries were also measured before and during selective adaptation (using all end-point stimuli as adaptors in separate sessions). Boundary shifts were obtained in the expected directions and magnitudes. The adaptive procedure is faster than the identification test and exhibits high test-retest reliability.

Studies of speech perception are often interested in estimating the perceptual boundary between two phoneme categories. Phoneme boundaries (e.g., Ganong & Zatorre, 1980) have usually been estimated by analyzing the results of identification tests. In these tests, members of a continuum of stimuli are presented for identification in random order. The identification functions describing the labeling responses express percent identification for each phoneme category as a function of the stimulus value along the continuum. The phoneme boundary (i.e., the stimulus value that is assigned to either category 50% of the time) is determined by means of interpolation or curve-fitting procedures.

Although in some instances, such as in studies on categorical perception, the whole identification function is of interest, in other investigations only an estimate of the phoneme boundary is of interest. In the latter case, the practice of obtaining full identification functions is time consuming and superfluous. Ganong and Zatorre (1980) addressed this issue and showed that equivalent estimates of phoneme boundaries may be obtained with different procedures, all requiring less testing time than the identification test. Various adaptive algorithms have been used to estimate phoneme boundaries in adults (Summerfield & Haggard, 1977), children (Elliott, Longinotti,

Meyer, Raz, & Zucker, 1981), and infants (Aslin, Pisoni, Hennessy, & Perey, 1981).

The time factor involved in the traditional method of estimating phoneme boundaries becomes most crucial in studies of selective adaptation for speech. This test necessitates the repeated presentation of a member of a stimulus continuum which alters the identification of some stimuli along the continuum. This effect, first described by Eimas and Corbit (1973), has usually been expressed as a shift in the location of the boundary toward the category of the adapting stimulus. The procedure involves two stages: First, a baseline (preadaptation) identification function is obtained, as described above, and the phoneme boundary is calculated. Next, a series of adaptation sessions is run. Every adaptation session retests the identification function. However, the presentation of stimuli for identification is interrupted during presentation of the adapting stimulus. The amount of adaptation on each trial and the frequency of the interruption range from 10 repetitions every item (Miller, Connine, Schermer, & Kluender, 1983) to 180 or more repetitions every 11 items (e.g., Cole, Cooper, Singer, & Allard, 1975). Following each adaptation trial, a new identification function is derived and the boundary is compared with the preadaptation boundary. Many investigators have reported adaptation sessions to last up to 2 h. The present study investigates the use of a simple up-down adaptive procedure (Levitt, 1971) to estimate the boundary between two phoneme categories and the shift in the boundary location resulting from the selective adaptation effect.

Two experiments will be reported. Experiment 1

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tested the hypothesis that direct estimates of phoneme boundaries obtained with a simple up-down adaptive procedure agree with those derived from complete identification functions. Experiment 2 tested the hypothesis that adaptive estimates of the shift in phoneme boundaries following selective adaptation correspond in terms of magnitude and direction to previous reports employing traditional testing procedures. All tests were conducted with two stimulus sets: a voicing (/ba/-/pa/) continuum and a place (/ba/-/da/-/ga/) continuum.

EXPERIMENT 1: BOUNDARY ESTIMATION

Before the simple up-down adaptive procedure could be used to measure a change in phoneme boundary following adaptation, it was necessary to determine whether the boundaries estimated with this method agreed with those derived from identification functions.

Method

Subjects. Twenty-two normal-hearing adults between the ages of 17 and 24 years participated in the experiments. The subjects were tested individually.

Stimuli. All stimuli were synthesized with an implementation (Kewley-Port, 1978) of a cascade terminal-analog speech synthesizer (Klatt, 1980). Stimuli were generated off-line and stored on magnetic disk. They were played at a rate of 10 kHz through a 14-bit D/A converter, low-pass filtered at 4200 Hz. Two stimulus continua were generated; a voicing continuum (13 stimuli changing from /ba/ to /pa/) and a place continuum (13 stimuli changing from /ba/ to /da/ and /ga/). All stimuli were 300 msec in duration and had five formants, with initial 40-msec transitions on the first three formants and a final, fixed location corresponding to the vowel [a].

In the voicing continuum, the fixed formant frequencies (and bandwidths) for the five formants were: 700 Hz (90 Hz), 1200 Hz (90 Hz), 2600 Hz (130 Hz), 3300 Hz (400 Hz), and 3700 Hz (500 Hz). Starting frequencies of the transitions to the first three formants were 400, 1000, and 2400 Hz. Voice onset time (VOT) values increased in 5-msec steps between stimulus 1 and 11 (VOT values of 0 and 50 msec, respectively) and were 60 and 70 msec for stimuli 12 and 13, respectively. VOT was controlled by preceding the onset of voicing with a 5-msec noise burst followed by aspiration equal in duration to the VOT selected for each stimulus. For stimulus 1, voicing onset coincided with the release of the noise burst. Voicing amplitude decreased linearly from full amplitude to full attenuation over the last 100 msec of each syllable. Fundamental frequency rose from 120 to 125 Hz during the first 50 msec of the syllable and then fell linearly to 100 Hz over the remaining steady-state portion of the vowel.

In the place continuum, the fixed frequencies (and bandwidths) for the five formants were 720 Hz (50 Hz), 1240 Hz (80 Hz), 2500 Hz (120 Hz), 3600 Hz (250 Hz), and 4500 Hz (300 Hz). The stimuli were constructed such that items 1, 7, and 13 were perceived as the best exemplars of /ba/, /da/, and /ga/, respectively. Starting frequencies for the second and third formant transitions were 942 and 1904 Hz for stimulus 1, 1700 and 2791 Hz for stimulus 7, and 1650 and 1904 Hz for stimulus 13, respectively. Starting frequencies for the second and third formant transitions for all other stimuli were interpolated to change in equal steps on a log-frequency scale. Starting frequency of the transitions to the first formant was 200 Hz for all stimuli. Voicing amplitude decreased linearly over a range of 40 dB during the last 50 msec of each syl-

lable. Fundamental frequency rose linearly from 103 to 125 Hz within the first 40 msec of voicing, dropped to 100 Hz within the next 180 msec, and then dropped to 50 Hz during the final 80 msec of each syllable.

Procedure. All subjects participated in two experimental tasks: identification and adaptive boundary estimation. In the identification task, all members of a stimulus continuum were presented 12 times in random order. Following each presentation, the listeners pressed a response button labeled with the phoneme category to which they assigned each stimulus (/ba/ or /pa/ for the voicing continuum, and /ba/, /da/ or /ga/ for the place continuum). Responses to the first two presentations of each stimulus were discarded, and those to the last 10 presentations were analyzed in terms of frequency of assignment of every stimulus to each phoneme category.

The second task involved a direct estimate of the boundary between two preselected phoneme categories using a simple up-down adaptive procedure. With this method, the stimulus to be presented on a given trial is determined by the listener's last response. For example, in estimating the /ba/-/da/ boundary, stimulus 3 was presented on the first trial. If it was labeled "ba," the next trial presented stimulus 4. If the response to stimulus 3 was "da," the next trial presented stimulus 2. The procedure converged on the phoneme boundary, increasing stimulus value following a "ba" response and decreasing stimulus value following a "da" response. Testing was terminated when 10 reversals in the direction of stimulus change were obtained. The boundary was determined by averaging stimulus values at the last eight reversal points. The same procedure was used to estimate the /da/-/ga/ and /ba/-/pa/ boundaries.

All subjects participated in a practice session followed by two experimental sessions. In each experimental session, two identification functions were obtained, one for the voicing and one for the place continuum. Then two adaptive estimates of all three phoneme boundaries were obtained. All tests within an experimental session were administered in random order. The identification responses obtained in both experimental sessions for each continuum were averaged to produce the final identification curve for every subject. The adaptive estimates of all phoneme boundaries in each session are based on the average of two independent runs.

Stimulus synthesis, subject-paced test administration, and response collection were controlled by a DEC PDP-11/40 minicomputer. Stimuli were presented monaurally via TDH-49 earphones mounted in circumaural cushions at an rms level of 85 dB SPL for a continuous synthetic vowel [a].

Results

The major goal of this experiment was to assess the validity of the adaptive phoneme boundary estimates in terms of their correspondence to the boundary values derived from identification functions. In addition, we were interested in evaluating the reliability of the adaptive procedure in this particular application.

A logistic curve (Bush, 1963) was fit to the identification functions obtained from each subject. The phoneme boundary was taken as the interpolated stimulus value that corresponded to a 50% response level on that curve. Table 1 shows group mean, standard deviation, minimum and maximum stimulus values for all phoneme boundaries as obtained by (a) identification functions, (b) adaptive estimation, and (c) replication of the adaptive procedure in a separate session. Values in (b) and (c) are based on the average of two runs per session.

Examination of Table 1 suggests a remarkably

Table 1
Mean, Standard Deviation (SD), and Minimum and Maximum Stimulus Values for Three Phonetic Boundaries, Interpolated from Curves Fitted to the Identification Functions (Identification) and Estimated (Up-Down) and Retested with the Adaptive Procedure

Boundary	Test	Mean	SD	Minimum	Maximum
ba-pa	Identification	6.138	.452	5.290	7.053
	Up-Down	6.196	.918	3.500	7.500
	Retest	5.621	.946	3.167	7.167
ba-da	Identification	4.852	.360	3.951	5.485
	Up-Down	4.834	.701	3.167	5.750
	Retest	5.057	.636	3.667	6.000
da-ga	Identification	10.008	.591	8.855	11.307
	Up-Down	9.955	.705	8.667	10.667
	Retest	9.807	.762	8.250	10.667

Note— $n = 22$.

Table 2
Pearson Product-Moment Correlations Between Adaptive Estimates and Their Replications (Up-Down/Retest) and Between Adaptive and Fitted Estimates (Up-Down/Identification) for Three Phoneme-Boundaries

Boundary	Up-Down/ Retest	Up-Down/ Identification
ba-pa	.7403	.5261
ba-da	.7652	.6021
da-ga	.8875	.7570

Note— $n = 22$, $p < .006$.

close agreement among all phoneme-boundary estimates for both the voicing and place continua. In fact, all mean values within a phoneme-category contrast are within less than one stimulus value apart. The observed strong relation is supported by the Pearson product moment correlations among the various estimates of each phoneme boundary shown in Table 2. Thus, we conclude that the simple up-down adaptive method may be reliably used to estimate the boundary between two phoneme categories.

EXPERIMENT 2: SELECTIVE ADAPTATION

This experiment addressed the main goal of the present study. The principle of simple up-down adaptive tracking was used to estimate changes in phoneme boundaries following adaptation. Subjects

and stimuli were the same as in the first experiment. All the data for Experiment 1 were collected prior to adaptation.

Method

Each subject participated in six sessions of approximately 30 min each, conducted on separate days. Every session included a baseline adaptive estimate of a particular phoneme boundary followed by an adaptation test. The adaptation test was identical to the baseline boundary estimation, except that it was interspersed with an adapting syllable. The adaptor was presented 200 times at the beginning of the test and 100 times following each block of eight test stimuli, with an interadaptor interval of 300 msec. The first test stimulus in each block was presented 2 sec following the termination of the last adaptor. Within each block, or adaptation trial, stimulus values to be presented were determined by the simple up-down rules described in the Procedure section for Experiment 1. Testing was terminated when 10 reversals in the direction of stimulus change were obtained across all adaptation trials. The boundary was determined by averaging stimulus values at the last eight reversal points. The amount of adaptation was calculated by subtracting the boundary value estimated during the adaptation test from that obtained in the baseline condition. Stimuli 1 and 13 of the voicing continuum served as adaptors for the /ba-/pa/ boundary, and stimuli 1 and 7 and stimuli 7 and 13 of the place continuum served as adaptors for the /ba-/da/ and /da-/ga/ boundaries, respectively, all in separate sessions.

Results

The amount of shift (in stimulus value) for all phoneme boundaries following adaptation is shown in Table 3. Positive mean values indicate a shift toward larger stimulus values, whereas negative mean values indicate a shift toward smaller stimulus values

Table 3
Mean, Standard Deviation (SD), and Maximum and Minimum Stimulus Values for the Amount of Shift in Three Boundaries After Adaptation with Various Stimuli

Boundary	Adaptor (Stimulus No.)	Mean	SD	Minimum	Maximum
ba-pa	ba (1)	-1.148	.599	-.250	-2.190
	pa (13)	2.337	1.172	.625	5.375
ba-da	ba (1)	-1.027	.512	-.167	-2.333
	da (7)	1.051	.329	.333	1.667
da-ga	da (7)	-1.385	.525	-.333	-2.500
	ga (13)	.954	.645	.125	2.250

Note— $n = 22$.

along the respective continuum. Examination of Table 3 suggests that our procedure consistently shows the expected adaptation effects for all adaptor-boundary combinations. The shifts in the boundary locations are always toward the adapting stimulus. Furthermore, as noted by Eimas, Cooper, and Corbit (1973), our voicing data show that a voiceless adaptor has a considerably larger effect on the voiced-voiceless boundary than does a voiced adaptor.

SUMMARY

The results of the present study suggest that the simple up-down adaptive procedure can be used to directly estimate the boundary location between two phoneme-categories. We have also shown that this procedure can be applied to measure selective adaptation to speech in sessions lasting about 10 min. The generality of our findings is supported by data obtained with three phoneme boundaries and two different stimulus continua. Although we measured selective adaptation effects at the phoneme boundary, within-category effects could be estimated with a transformed up-down method (Levitt, 1971) by converging on different points on the psychometric curve.

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