Control of pharyngeal cavity size for English voiced and voiceless stops

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This study reports on pharyngeal cavity size change mechanisms associated with voiced–voiceless stop contrast in English. Electromyographic recordings were obtained from pharyngeal and infrahyoid muscles of three speakers, using bipolar, hooked-wire electrodes. The emg potentials were sampled and averaged under computer control. The utterances sampled were 27 pairs of nonsense disyllables that contrasted only in the voicing of one stop consonant. All the English stop cognate pairs were included. Two modes of expanding the pharynx for voiced stops are proposed, each applying to a different group of muscles; an "active" mode, requiring increased muscle activity to expand the pharynx; and a "passive" mode, requiring suppression of muscle activity to expand the pharynx. The data reveal different patterns of use of the two expansion modes for the three subjects. The results are discussed in terms of current phonological theory.

Subject Classification: 70.20, 70.70.

INTRODUCTION

A long controversy surrounds the question of what constitutes the primary distinction between homorganic stops in the languages of the world. Without reviewing the literature exhaustively, one might contrast the views of Rousselot (1924) and Lisker and Abramson (1964). Rousselot suggested that the primary difference between pairs of French stops is one of tension in the peripheral articulators—that is, the difference is extralaryngeal. In contrast, Lisker and Abramson, in an examination of a number of languages were able to show that almost all the differences among sets of stops could be accounted for by differences in the timing of the onset of glottal pulsing relative to the release of stop occlusion—that is, the differences are essentially at the laryngeal level. A more elaborate theory has been proposed by Chomsky and Halle (1968). In their formulation, the timing of the onset of glottal pulsing is a consequence of the interaction of four features—some laryngeal and some extralaryngeal: (1) tense–nontense; (2) heightened subglottal pressure; (3) voiced-nonvoiced; and (4) glottal constriction. This paper will be concerned with the tension feature, as it pertains to adjustment of pharyngeal cavity size.

Physiological researchers looking for this tension difference (usually in English) have found it elusive. Measures of the mechanical pressure of the lip (Malécot, 1966a; Lubker and Parris, 1970) were equivocal for /p/ and /b/. However, the area of tongue contact on the hard palate for alveolar stops (Fujimura, 1973) is greater for /t/ than for /d/, although this study was done with Japanese as the language base. Measures of peak intraoral air pressure (Malécot, 1955, 1966b, 1970; Arkebaur *et al.*, 1967; Netsell, 1969; Lubker and Parris, 1970; Tatham and Morton, 1969, 1973; Warren and Hall, 1973) have generally shown greater pressure for /p/ than for /b/. However, Lisker (1970) has shown that peak intraoral air pressure is not sufficient for categorizing prestress English stop cognates, as the peak pressures reached are quite similar. What is distinctive, however, is the function of the growth in pressure, with the pressure rise nearly instantaneous after closure for the voiceless stops, and a staircase function for the voiced stops (incrementing with each glottal pulse) up to the same pressure level achieved for the voiceless stops. Netsell (1969) has demonstrated negligible differences in subglottal pressure between the English voiced and aspirated voiceless stops /t/ and /d/. Malécot (1970), suggesting that the feature "tenseness" must have some reality since naive subjects so readily respond to it, believes that intraoral air pressure differences account for the distinction, but only indirectly; that is, the feature fortis–lenis (tense–lax) is a synesthetic interpretation of the evident air pressure differences. In light of Lisker's (1970) data, however, this view needs modification: the shape of the function of pressure growth may be the cue for the feature.

Several additional physiological studies have been undertaken to determine whether there are differences in the strength of the electromyographic signal among voiced and voiceless stops at the place of vocal tract occlusion. Harris *et al.* (1965), Fromkin (1966), Tatham and Morton (1969), and Lubker and Parris (1970) have reported finding no consistent difference in EMG peak strength between /p/ and /b/. Tatham and Morton (1973), though, have reported small but significant differences in EMG signal strength at the point of release of /p/ and /b/. Other investigators have looked for this tension difference elsewhere in the vocal tract, specifically in the pharyngeal cavity. Rothenberg (1968) calculated the maximum possible expansion of the pharynx (accounting for anteroinferior movement of the tongue, retraction of the lateral and posterior pharyngeal walls, and lowering of the larynx) at 10.0 ml. He assumed each 1.0 ml of volume increase will allow glottal pulsing to continue for an additional 10 msec, and arrived at a figure of 100 msec as the maximum possible duration of glottal pulsing during stop occlusion as a result of pharyngeal cavity expansion. He also suggested that the velum might be sufficiently depressed for voiced stops to allow nasal escape of air during stop closure. The reported difference in tongue contact area for /t/ and /d/ (Fujimura, 1973) may be an indication of greater oral cavity volume for /d/ than for /t/. Both Perkell (1969) and Kent and Moll(1969) measured pharyngeal cavity dimensions from lateral cinefluorographic films for English stop cognate pairs. Both found an increase in the anteroposterior and vertical dimensions of the pharynx for the voiced stops over the dimensions observed for the voiceless stops. Such a volume increase in the pharyngeal cavity occurring during the stop occlusion would result in a drop in supraglottal pressure that would aid the maintenance of the transglottal pressure differential necessary for the continuation of glottal pulsing through the period of vocal tract occlusion. Perkell assigns the volume increase to reduced tension in the pharyngeal wall musculature for the voiced [−tense] stops included in his utterance set, allowing the pharyngeal walls to retract. He notes, too, that the larynx is lower for the voiced stop than for the voiceless stop. Perkell's data also show an increase in velar height during the voiced stop occlusion over that observed for the voiceless stop. Kent and Moll suggest that both the anteroposterior and vertical dimension increases might be due to the action of a muscle that would draw the hyoid bone, and consequently the larynx, inferiorly, arguing that this would also have the effect of drawing the base of tongue anteroinferiorly, increasing the anteroposterior dimension of the pharyngeal cavity.

This work is directed to the proposed feature [±tense] (Chomsky and Halle, 1968) and identifying the pattern of pharyngeal muscle activity associated with the observed pharyngeal cavity expansion for voiced stop consonants.

I. PROCEDURES

A. Subjects

The three available volunteer subjects used in this study each spoke a different dialect of American English, but were judged to be without notable speech defects and were trained to maintain stable list articulation.

Each subject served twice, with the two experimental sessions for each subject separated by six months to one year, resulting in a total of six experimental sessions. At the first session an attempt was made to record from each muscle included in the experiment. The second experimental session was used to obtain satisfactory recordings from muscles whose earlier data were unsatisfactory, and then to duplicate data from as many muscles as there were remaining recording channels. Thus at least one good recording was obtained from each muscle for each subject. For those cases where duplicate recordings were made, the patterns (though not, of course, the absolute levels) of EMG activity remained reasonably constant over the two sessions.

B. Electrodes: preparation and insertions

Bipolar hooked-wire electrodes were used throughout. The electrodes and the insertion techniques employed were those described in Hirose (1971).[1]

In general a modification of the hooked-wire electrode was used. Insertions were made with the subject under minimum local anesthetic. Electrode and subject preparation are described at greater length in Bell-Berti (1973) and Hirose (1971).

Insertions to velopharyngeal muscles were always peroral, made with an angulated needle, and with the subject in a sitting position. Insertions to the sternohyoid, one of the strap muscles of the neck, were percutaneous, made with a straight needle, and with the subject in a supine position.

Levator palatini. The insertion was made into the levator "dimple" on the soft palate while the subject sustained open vowel phonation. The tip of the needle was directed latero-cranio-posteriorly approximately 10 mm from the surface of the mucosa. Verification of electrode placement was made by having the subject repeat the production of /s/. Marked activity is observed for this strongly oral gesture if the electrodes are properly placed.

Superior constrictor. The tip of an angulated electrode-bearing needle was directed cranially to reach the posterior pharyngeal wall at a position lateral to the midline at the estimated level of velopharyngeal closure. As the insertion was made under direct inspection, placement was verified if EMG activity was observed for swallowing.

Middle constrictor. The insertion was made using an angulated needle directed caudally into the posterior pharyngeal wall near the level of the tip of the epiglottis, while the subject's tongue was protruded and held for improved visualization of the insertion site. As the pharyngeal constrictor muscles are interlayered in the transition from one to another, precise discrimination of the superior and middle constrictor fibers is not possible. Hence, we examined, under the name "middle constrictor," a topographical representation of the pharyngeal constrictor at the anatomical site described. Electrode placement was again verified if EMG activity was observed for swallowing.

Sternohyoid. The insertion was made at the level of the thyroid lamina, where the contour of the muscle is visible when the subject, in a supine position, raises his head. At this level, possible contamination by other muscles is kept to a minimum. The needle was inserted lateral to the midline, parallel to the alignment of the muscle fibers, as the subject raised his head. Electrode placement was verified if strong EMG activity was observed while the subject raised his head, opened his jaw, or produced very low-frequency phonation.

C. Experiment: utterance types and protocol

The distinction between voiced and voiceless stops in English may be viewed as a timing difference between laryngeal and supralaryngeal gestures (Lisker and Abramson, 1964). In the voiced stops, voicing does not usually begin until after the release of an initial

TABLE I. Experimental disyllabic nonsense utterances, containing voiced-voiceless cognate contrasts in each of three vowel environments in both stop-nasal (18 utterances—9 voiced versus voiceless minimal pairs) and nasal-stop (36 utterances—18 voiced versus voiceless minimal pairs) combinations.

Stop-nasal utterances		
/fipmip/–/fibmip/	/fapmap/–/fabmap/	/fupmup/–/fubmup/
/fitmip/–/fidmip/	/fatmap/–/fadmap/	/futmup/–/fudmup/
/fikmip/–/figmip/	/fakmap/–/fagmap/	/fukmup/–/fugmup/
Nasal-stop utterances		
/fimpip/–/fimbip/	/fampap/–/fambap/	/fumpup/–/fumbup/
/fimtip/–/fimdip/	/famtap/–/famdap/	/fumtup/–/fumdup/
/fimkip/–/fimgip/	/famkap/–/famgap/	/fumkup/–/fumgup/
/fiŋpip/–/fiŋbip/	/faŋpap/–/faŋbap/	/fuŋpup/–/fuŋbup/
/fiŋtip/–/fiŋdip/	/faŋtap/–/faŋdap/	/fuŋtup/–/fuŋdup/
/fiŋkip/–/fiŋgip/	/faŋkap/–/faŋgap/	/fuŋkup/–/fuŋgup/

stop (Lisker and Abramson, 1964), and frequently does not persist to the end of the occlusion of a final stop (Bronstein, 1961). The result of the voicing distinction being manifested as a timing distinction, then, is that voicing may not occur during the occlusion of initial and final stops. However, in medial position this temporal distinction is manifested as the continuation or interruption of glottal pulsing during the occlusion (Lisker and Abramson, 1964, 1967). Since we were interested in describing the pattern of pharyngeal muscle control accompanying this voicing difference, we used the voicing case in which pharyngeal expansion was most likely to occur—the one in which glottal pulsing is continuous through the occlusion—with the stops in medial position. A set of nonsense disyllables was constructed, to contain the six English stop consonants, /p, t, k, b, d, g/, in medial position, the nasal consonants /m, ŋ, /, and the vowels /i, ɑ, u/. The same vowel occurred in both syllables of each disyllable, which contained a stop-nasal (18 utterance types) or a nasal-stop (36 utterance types) sequence in medial position (Table I). The first syllable received primary stress, and the second syllable received secondary stress. Some elements of the experimental design were included as part of a larger investigation.[2]

In electromyographic investigations it is not advisable to inspect the EMG potentials of the utterance initial gesture as its timing and magnitude may both be affected by a readying of the articulators well before speech begins. As we wished to study velopharyngeal activity for vowels, the utterance format had, therefore, to include an additional phoneme before the vowel under study. The labial consonant /f/ was selected to give all the utterances an initial oral articulation which did not involve the tongue, and so probably would not create any carryover coarticulation effects in the following vowel. All utterances ended with /p/, a labial consonant, to avoid anticipatory lingual coarticulation effects, to control the length of the final vowel, and to insure a terminal oral articulation. The initial and final consonants were voiceless to facilitate the identification of the vowel onset and termination from an oscillographic record of the speech waveform used to obtain measurements of segment duration.

Four randomizations of the 54 experimental utterances were read four times by each subject, providing 16 repetitions of each utterance type for the subsequent analysis.

D. Data collection and processing system

The Record–Playback System. The data were collected and processed using the Haskins Laboratories EMG system described by Port (1971; Kewley-Port, 1973). The electrodes were connected to differential preamplifiers with gains of 40 dB. The signals were then fed to distribution amplifiers having adjustable gains and including 80-Hz high-pass filters, with 24-dB/octave rolloff; the low-frequency filtering is intended to reject hum and movement artifacts. The signals were FM recorded on 1-in. magnetic tape using a Consolidated Electrodynamics VR-3300 14-channel instrumentation recorder. The acoustic signal and appropriate clock and code pulses for data processing were recorded as AM signals.

The recorded signals were played back through the distribution amplifiers and routed through a section of the 80-Hz high-pass filter, resulting in 36 dB/octave total rolloff. The overall frequency response for the FM channels was essentially flat for the frequency range 80–1250 Hz, with a signal-to-noise ratio of about 40 dB.

After recording, the electromyographic, voice, and code tracks were input to a Honeywell Visicorder, whose oscillographic records were used for visual editing of the signals and determining the segment durations of the vowels and medial consonants of the experimental utterances. The EMG signals were inspected for nonphysiological spike potentials. The point in the audio signal selected for lining up the utterances for computer sampling and averaging was the beginning of the acoustic signal for /m/ in the stop-nasal utterances, the end of the acoustic signal for /m/ and /ŋ/ in the nasal-stop utterances.

The EMG data tape was played back on the same 14-channel tape recorder under computer control. The analog EMG signals were full-wave rectified and passed through an RC circuit that performed a running integration with a time constant of 25 msec. The signals were sampled at 5-msec intervals. The stored digital sample values were converted to microvolt values by comparison with the 300-μV calibration signal. The conversion factors were calculated and stored on the digital tape along with the digital sample values for the experiment. The sums for each utterance type were computed and stored on the digital tape. The means were calculated and printed out for the 5-msec intervals at which the analog data were sampled.

II. RESULTS

A. Preliminary

The present data bear on stop consonant voicing because these phonetic variations are associated with variations in the volume of the pharyngeal cavity (Perkell, 1969; Kent and Moll, 1969). This volume will be increased by contraction of palatal muscles and the sternohyoid, and decreased by contraction of the muscles of the posterior and lateral pharyngeal walls. If voiced stop consonants are associated with an increase in volume of the pharyngeal cavity (Perkell, 1969; Kent and Moll, 1969), we should observe greater activity in the levator palatini and/or the sternhyoid, and less activity in the posterior and/or lateral pharyngeal wall musculature (superior and middle constrictors, palatopharyngeus, and palatoglossus), for these stops than for their voiceless cognates.

An alternative possibility would be that voiceless stops would be associated with greater tension in all, or some, of the pharyngeal musculature, as suggested by Chomsky and Halle.

B. Data for a subject

The EMG potentials are accessible in both graphic (Fig. 1) and digital (microvolt values at 5-msec intervals) format. The EMG potentials associated with the medial stop consonant (the peak in the EMG curve indicated by the arrow) were compared for pairs of utterances differing only in the voicing of that stop.[3] A tally was kept of the number of times the difference in EMG potential indicated pharyngeal cavity expansion for the voiced cognate. There were, generally, 27 comparisons for each electrode placement for each subject.[4]

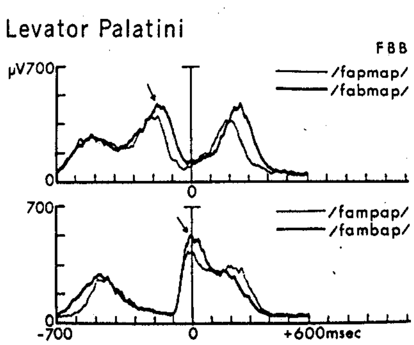

FIG. 1. Sample graphic displays of EMG data curves from the levator palatini for one subject (FBB).

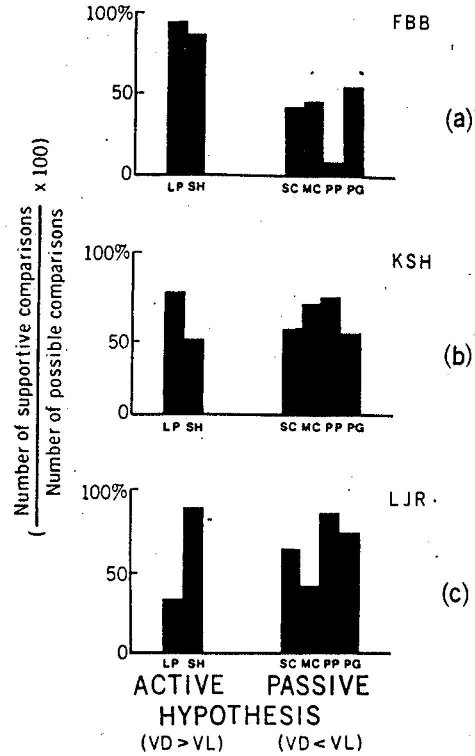

FIG. 2. Intrasubject variation in patterns of pharyngeal muscle activity for pharyngeal cavity expansion for voiced stop consonant production. Ordinate values are the percentage of hypothesis-supporting cases. (LP: levator palatini; SH: stern sternohyoid; SC: superior constrictor; MC: middle constrictor; PP: palatopharyngeus; PG: palatoglossus.)

Subject FBB. Levator palatini and sternohyoid potentials were higher for the voiced stops than for their voiceless cognates in 93% ($P < 0.0001$) and 87% ($P < 0.0001$) of the comparisons, respectively [Fig. 2(a)]. Superior- and middle-constrictor, palatopharyngeus, and palatoglossus potentials were lower for the voiced stops than for their voiceless cognates in 41%, 44%, 7% ($P < 0.0001$), and 54% of the comparisons, respectively [Fig. 2(a)]. We have, as yet, no explanation for the reversal of the expected pattern of palatopharyngeus activity by this subject.

Subject KSH. Levator palatini and sternohyoid potentials were higher for the voiced stops than for their voiceless cognates in 74% ($P < 0.05$) and 46% of the comparisons, respectively [Fig. 2(b)]. Superior- and middle-constrictor, palatopharyngeus, and palatoglossus potentials were lower for the voiced stops than for their voiceless cognates in 54%, 70% ($P < 0.05$), 74% ($P < 0.05$), and 50% of the comparisons, respectively [Fig. 2(b)].

Subject LJR. Levator palatini and sternohyoid potentials were higher for the voiced stops than for their voiceless cognates in 31% ($P < 0.05$) and 89% ($P < 0.0001$) of the comparisons, respectively [Fig. 2(c)]. Superior- and middle-constrictor, palatopharyngeus, and palato-

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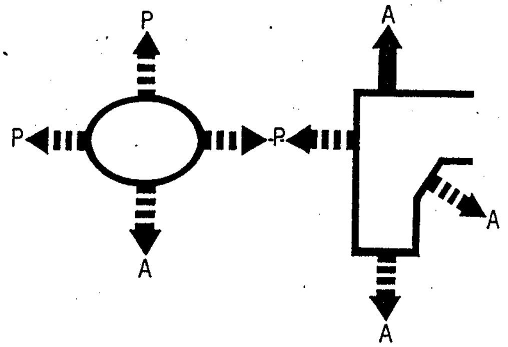

FIG. 3. Schematic drawings of the pharyngeal cavity: transverse (left) and midsagittal sections. Possible directions for expansion are indicated. (A: expansion via the "active" mode; P: expansion via the "passive" mode.)

glossus potentials were lower for the voiced stops than for their voiceless cognates in 65%, 41%, 87% ($P < 0.001$), and 74% ($P < 0.005$) of the comparisons, respectively [Fig. 2(c)].

C. Active and passive pharyngeal expansion

Since greater activity in the levator palatini and sternohyoid muscles would lead to an increase in pharyngeal cavity size, we might call use of these muscles to increase pharyngeal volume the active expansion mode. Conversely, since less activity in the constrictor and faucal pillar muscles would also lead to an increase in pharyngeal cavity size, we might call the inhibition of these muscles to increase pharyngeal volume the passive expansion mode (Fig. 3). Reexamining the data within this framework, we see that each subject uses at least one of the active expansion mode muscles significantly often, and one subject (FBB) uses both of these muscles significantly often.

However, one subject (FBB) never uses any of the passive mode muscles significantly often, and one subject (LJR), who used an active mode muscle significantly less often for voiced stops, used the passive mode muscles more often.

The use of different patterns of active and passive expansion is seen clearly in Fig. 4. The subjects using active expansion less often (LJR and KSH) use more passive expansion, while the subject using active expansion more often (FBB) uses less passive expansion.

III. DISCUSSION

A. Individual differences

The data reveal different patterns of muscle activity for each of the three subjects: each uses a different arrangement of muscle activities to achieve the pharyngeal cavity expansion necessary for the continuation of glottal pulsing during voiced stop consonant occlusion.[5] We do not know the cause of the intersubject differences in the pattern of pharyngeal cavity expansion: they might be idiosyncratically learned behaviors or they might be anatomically based differences. Resolution of this point awaits further study.

B. Active and passive expansion modes

The Chomsky and Halle (1968) feature [± tense] postulates less vocal tract wall rigidity for voiced stops than for their voiceless cognates. Regardless of the systematic uses made of this feature, they find the sole physiological support for their argument in Perkell's (1965) data on pharyngeal cavity width. The pharyngeal cavity expansion accompanying voiced stop articulation is, then, in that system, an essentially passive mechanism, with relaxation of the muscles resulting in retraction of the posterior and lateral pharyngeal walls. It is for this reason that we have termed expansion caused by reduced pharyngeal wall muscle activity the "passive" expansion mode. On the other hand, when the expansion results from the increased activity of some muscle or group of muscles, it might logically be considered an "active" expansion mode.

It appears, from these data, that an adequate description of pharyngeal cavity expansion for voiced stop articulation is neither an exclusively active nor an exclusively passive one. Each speaker uses both modes of enlargement, while apparently favoring one mode over the other. Indeed, for two of the speakers the levator palatini is more active for the voiced, [– tense], stops than for the voiceless, [+ tense], stops, and for two speakers the sternohyoid is more active for the voiced, [– tense], stops than for the voiceless, [+ tense], stops, which is in contradiction to the general notion of "tenseness."

It is clear, then, that the feature [± tense] is inadequate for describing the pharyngeal volume changes concomitant with voicing distinctions, as that feature at best explains the larger portion of some speakers pharyngeal adjustments and never explains the full measure of enlargement.

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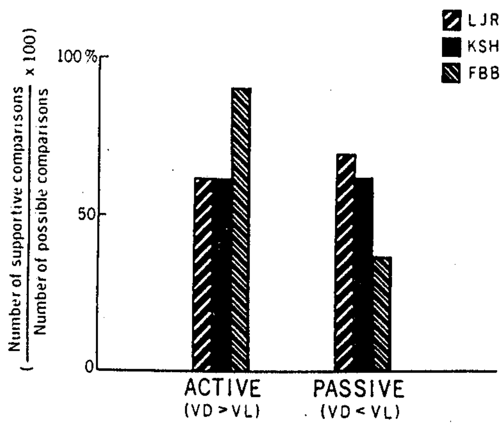

FIG. 4. Intersubject variation in modes of pharyngeal cavity expansion for voiced stop consonant production. The "active" mode includes the levator palatini and sternohyoid muscles; the "passive" mode includes the superior constrictor, middle constrictor, palatopharyngeus, and palatoglossus muscles.

City University of New York, in partial fulfillment of the requirements for the Ph. D. degree.

[1]The wire employed is a platinum–iridium alloy (90%–10%), of of 0.002-in. diameter, with an Isonel (polyester) coating (Consolidated Reactive Metals, P 91).

[2]These data were collected to investigate both pharyngeal cavity expansion and oral and nasal articulation mechanisms. The data to the latter point are reported elsewhere (Bell-Berti, 1973; Bell-Berti, in press).

[3]When obvious peaks of EMG activity could not be found for some muscles, the EMG values were taken at the time of peak levator palatini activity, which was always clear.

[4]There were only 20 comparisons for the superior constrictor placement for subject FBB.

[5]Spectrograms of a sample of three tokens of each utterance type for each subject showed voicing to be continuous through the stop closure, with the exception of utterance types containing /g/, that had occasional instances of voicing breaks during stop closure. It is desirable to make a more detailed study at some time on the conditions causing variation in closure voicing, but the present study does not include the pressure data essential to this work.

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