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Scaling of Glottal Opening[1]

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Abstract. Laryngeal control occurs mainly along two dimensions. One involves the longitudinal tension of the vocal folds and is used for control of fundamental frequency. The other involves abduction/adduction of the folds. This dimension is used in the vegetative functions of the larynx and in its phonetic function to control voicing and aspiration as well as voice quality. Although fine adjustments in timing of abduction/adduction gestures relative to supralaryngeal events produce contrasts of aspiration in obstruents, variations in the size of these gestures appear to be less significant and less finely controlled. The present experiment explores the control of laryngeal abduction/adduction by examining to what extent speakers can control size of glottal aperture under different conditions, with and without suitable feedback. The results suggest that voluntary control of the size of glottal opening is rather poor, and that subjects are unable to make very fine-graded adjustments along this dimension. Voluntary control of glottal opening in isolation is limited, perhaps because normal activities seldom require separate control of this variable. Instead, control of glottal opening is tightly coupled to such other activities as respiration, swallowing and speech articulation. Even in the context of sound production, glottal aperture is poorly controlled, perhaps because the precise degree of opening (as opposed to precise timing of opening and closing) has comparatively little practical significance over a wide range of openings.

Introduction

Laryngeal control occurs mainly along two dimensions. One involves the longitudinal tension of the vocal folds and is used for control of fundamental frequency. It is used extensively for linguistic purposes [FROMKIN, 1978], and speakers normally have a very fine-graded control along this dimension [e.g., SUNDBERG, 1979]. The other dimension involves abduction and adduction of the vocal folds. This dimension is

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used in the vegetative functions of the larynx and in its phonetic function to control voicing and aspiration as well as voice quality. Within the class of voiceless obstruents, the timing of abduction-adduction gestures in relation to supralaryngeal articulations is used to control aspiration. Different timing relationships between laryngeal abduction/adduction and oral closing/opening produce contrasts of preaspirated, unaspirated and postaspired obstruents [LÖFQVIST and YOSHIOKA, 1981, a, b].

While timing of opening and closing is thus linguistically significant, the size of the opening seems to be less significant as an independent parameter. Inspection of published records indicates that glottal aperture during speech seldom remains static for any appreciable duration, and it also varies significantly through the respiratory cycle. Furthermore, during the laryngeal gestures for unvoiced obstruents, speakers rarely seem to use more than two or three consistently distinct degrees of peak glottal opening. Under comparable conditions, a large opening seems to be associated with voiceless fricatives, a smaller opening is used for voiceless postaspirated stops, and voiceless unaspirated stops can have an even smaller opening. However, there do not seem to be any phonetic segments contrasted only by size of glottal aperture, except for voiced-voiceless pairs. Even when glottal openings of different sizes consistently seem to occur for different segments, as in aspirated and unaspirated stops in Hindi [KAGAYA and HIROSE, 1975], Icelandic [LÖFQVIST and YOSHIOKA, 1981 b] and Korean [KAGAYA, 1974], variations in interarticulator timing always appear to accompany the size differences. During phonation, however, fine adjustments along the abduction-adduction dimension may be used to regulate voice quality. Admittedly, the tentative conclusion that glottal aperture has little independent status is based on a small number of studies involving few languages, few speakers and limited speech materials. There are, moreover, technical problems in making measurements of glottal opening, since neither of the two most commonly used methods for laryngeal observation, fiberoptic filming and transillumination, can be calibrated at present. This problem can be solved, in principle, by the introduction of a stereofiberscope [FUJIMURA et al., 1979].

The preceding discussion indicates that glottal aperture is rarely controlled independently, and that the independent control that is used is mostly rather gross in nature, differentiating the classes closed, voicing and open. Voluntary control of this variable, furthermore, has not been previously studied. The present study, therefore, was designed to further explore the control of laryngeal abduction and adduction by examining to what extent speakers can control size of glottal aperture under static and dynamic, speech, and nonspeech conditions, with and without suitable feedback.

Method

The experimental procedure required subjects to produce different degrees of glottal opening under various conditions with and without feedback of opening size. Two subjects were tested. Laryngeal adjustments were monitored simultaneously by a fiberscope and by transillumination. A flexible fiberscope was introduced through the nose and held in position by a headband. The light from the fiberscope passing through the glottis was sensed by a phototransistor placed on the neck just below the cricoid cartilage. The transistor was coupled to the skin by a light tight enclosure and held in position by a neckband. The transillumination signal was recorded on magnetic tape together with a microphone signal. During the experimental session, the view of the glottis was constantly monitored through the fiberscope to detect movements and fogging of the fiberscope lens. In addition, the larynx was filmed at a film speed of 60 frames/s during selected intervals as a further control.

The subjects were instructed to produce different degrees of glottal opening with and without visual feedback of the transillumination signal under various static and dynamic speech and nonspeech conditions. Subjects were allowed to familiarize themselves with the experimental procedure but were not given extensive practice.

In the feedback condition, the subject monitored the transillumination signal on an oscilloscope. Four different levels of glottal aperture were defined on the oscilloscope screen, and the subject was instructed to make glottal openings corresponding to these levels. The levels were spaced at equal steps and ranged from an opening somewhat smaller than that found in voiceless sound production to one that might occur during inspiration. The levels were defined separately for each subject. Since neither transillumination nor fiberoptic filming can be calibrated, comparisons should only be made within an experimental session.

Pilot experiments revealed that the task of voluntarily controlling glottal opening in isolation (i.e., without coordinated sound production or respiratory activity) was very difficult or impossible. A constant static opening could not be maintained very well even with feedback and when simultaneous sound production or respiration was allowed. In order to make the task more manageable, subjects were therefore asked to match a target level by varying the peak opening in repeated dynamic opening-closure gestures. In most parts of the experiment, control of glottal aperture was accompanied by sound production or respiratory maneuvers. During many of these sessions, oral pressure was monitored in addition to the transillumination signal. This pressure was recorded through a catheter inserted pernasally into the pharynx, and the resulting signal was recorded on magnetic tape along with the transillumination and audio signals.

Results

Sample records of transillumination and oral pressure are given in figures 1 and 2. In figure 1, the subject produced repeated /s/ sounds

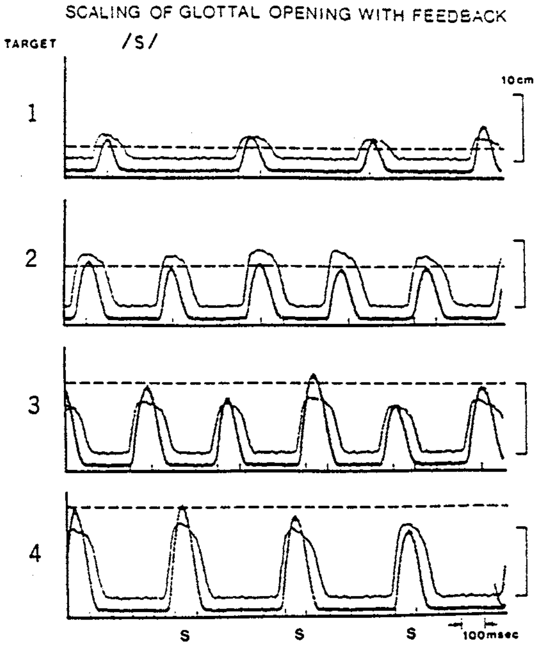

Fig. 1. Records of oral pressure (—) and transillumination (—) during scaling of glottal opening with visual feedback in isolated fricative production. Broken lines indicate the intended target levels.

with visual feedback of glottal opening trying to match the different target levels, indicated by broken lines. Voiceless obstruents, generally, have openings between levels 1 and 2. Figure 2 presents the same signals during attempts by the same subject to produce a given glottal aperture during the production of an intervocalic (stressed) voiceless fricative.

These two figures demonstrate some features that were common to the two subjects tested. Neither could make very accurate matches of the different degrees of opening. There was a tendency towards overshooting for the smaller target levels and undershooting for the larger ones. In the following, we will concentrate on the subjects' ability to produce distinct glottal openings without reference to their deviations from the actually intended targets.

In addition to the subjects' inability to produce constant sustained glottal openings, another finding is worth mentioning. It proved exceedingly difficult for the subjects to voluntarily produce glottal open-

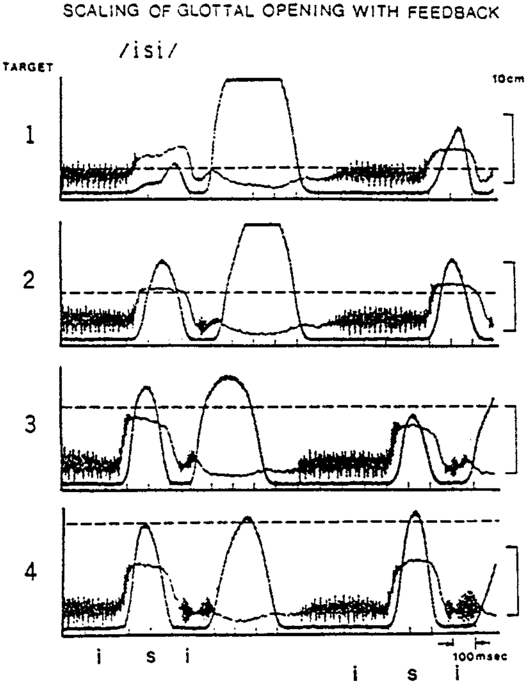

Fig. 2. Oral pressure (—) and transillumination (—) during scaling of glottal opening in CVC syllable production.

ings of different size without any prior experience of visual feedback. Thus, when asked to make a, subjectively, full glottal opening and then an opening half of the full size, subjects could only produce openings of similar and completely overlapping sizes. This held true for dynamic adjustments with or without sound production.

Figure 3 presents results from one subject during scaling with visual feedback with and without sound production. The sound produced was short isolated fricatives. The different target openings are indicated along the x axis. The y axis shows peak glottal opening in arbitrary units. Means and standard deviations are plotted. In this case, voiceless obstruents have glottal openings corresponding approximately to target levels 1 and 2. Evidently, the results are better with than without sound production. Even in the sound condition, however, levels 2 and 3 could not be distinguished. In the no-sound condition only level 1 was consistently differentiated, whereas the other three levels showed

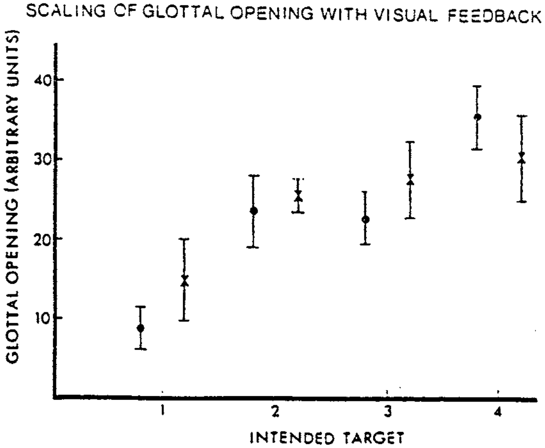

Fig. 3. Means and standard deviations of glottal opening in scaling with (●, /s/) and without (×) sound production. The measurements are based on 20–25 tokens in each condition.

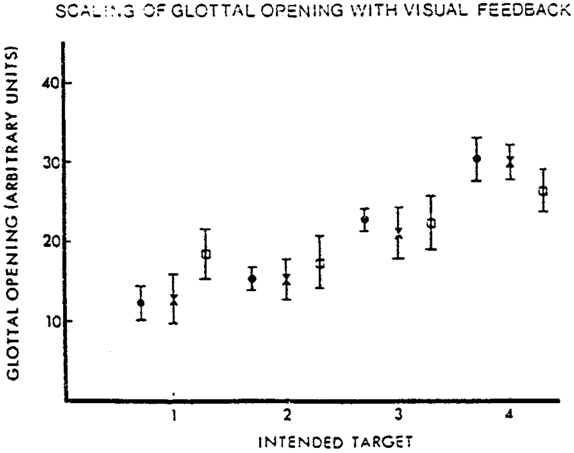

Fig. 4. Means and standard deviations of glottal opening in scaling with different types of sound production (● = /C/; × = /CV/; □ = VCV). The measurements are based on 15–20 tokens in each condition.

considerable overlap. Also, standard deviations are generally larger for the no-sound condition.

Figure 4 shows the results from the other subject for isolated fricative production and fricatives in CV and VCV syllables. Performance is better for the isolated fricatives, although even here levels 1 and 2 are not clearly distinguished. In the syllable condition, levels 1, 2, and 3 were not distinguishable.

Figure 5 shows data from the same subject for isolated fricatives with visual feedback and with feedback removed. Visual information obviously contributes to a better performance, since the results are much worse when feedback has been removed. In the no-feedback condition, levels 2, 3, and 4 overlap completely.

It is apparent from figures 1 and 2 that oral pressure and glottal opening tend to covary. When subjects tried to produce larger glottal openings, oral pressure increased. The relationship between glottal aperture and oral pressure is presented in figure 6 for all trials of one subject. A positive relationship is seen with a Pearson product moment correlation coefficient of 0.79 ($n = 28$). In order to further elucidate possible dependencies between pressure and opening, the subject was given visual feedback of the pressure signal and instructed to produce oral pressures of predetermined magnitudes. This was an easy task. The relationship between oral pressure and glottal opening during scaling of oral pressure is indicated by the crosses in figure 6. Also in this condition, a positive correlation between the two variables is found.

Discussion

Studies of movement scaling and movement reproduction with and without visual and kinesthetic feedback of the arms, the legs, the hands, and the fingers have usually shown good accuracy in the control of these structures [e.g., Lloyd and Caldwell, 1965; Marteniuk et al., 1972; Kelso and Wallace, 1978]. Similarly, scaling studies of supralaryngeal articulators such as the tongue and the lips [Chuang and Abbs, 1979; Porter and Lubker, 1980] indicate much finer control than that found for glottal aperture in the present experiment. In this respect, the larynx would seem to be more like the velum, since scaling of velar elevation has been reported to be rather poor [Shelton et al.,

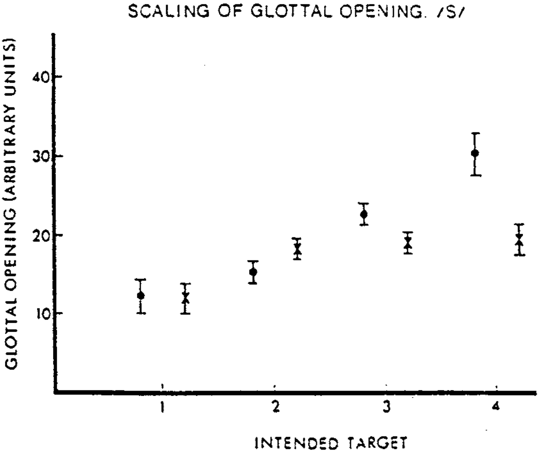

Fig. 5. Means and standard deviations of glottal opening in scaling with (●) and without (+) visual feedback. The measurements are based on 15–20 tokens in each condition.

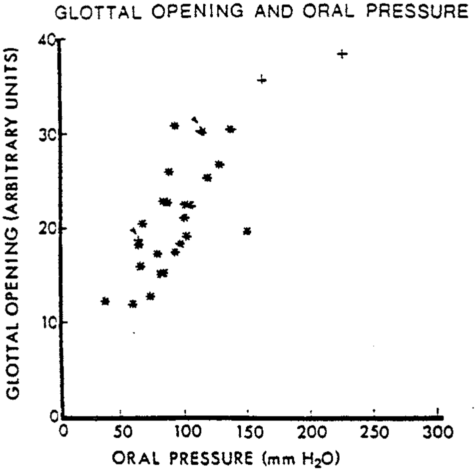

Fig. 6. Oral pressure plotted versus glottal opening during scaling of glottal opening (*) and oral pressure (+). Each data point represents the mean of 15–20 tokens during scaling of glottal opening, and 10–15 tokens during scaling of oral pressure.

1970]. At the same time, the study of the velum indicated that subjects were quite accurate in controlling the timing of velar movements.

The present results thus suggest that voluntary control of the size of glottal opening is rather poor. We should add a qualification, however, in that the effect of extensive training was not explored in the present study; performance may very well improve with practice. With this qualification, the control of glottal aperture would seem to be more coarse than that of other articulators investigated.

Visual feedback of glottal aperture obviously improves performance, but air pressure and airflow may also provide additional information. Also, auditory feedback may be used, at least during sound production. This is most likely the reason why scaling was better with than without sound production. The strategy adopted by the subjects was essentially that of changing the intensity of the frication noise. Glottal opening thus seemed to be controlled indirectly by varying expiratory effort, as evidenced by the close relationship between glottal opening and oral pressure. Since oral pressure is related to the intensity of the frication noise, auditory feedback could thus also be used as another channel of information.

A close relationship between glottal aperture and oral pressure is evident in figure 6. Therefore, it is possible that glottal opening was changed as a passive response to increased air pressure in the glottis. In order to test this possibility, sudden and unexpected pushes were applied to the chest of one subject during breathing and sustained fricative production. As a result of the pushes, oral pressure increased rapidly, but the associated change in glottal opening was very small, indicating that passive changes due to aerodynamic forces could not in themselves account for the results obtained in the scaling experiments. Thus, oral pressure and glottal aperture appear to be controlled synchronously.

The present results indicate that the control of glottal opening is intimately tied to other types of activities. Glottal aperture can thus most easily be controlled when the glottal movements occur as part of another event, such as respiratory maneuvers and speech. An illustration of this is the relationship between oral pressure and glottal opening in figure 6, where the same relationship holds if control is focussed on the glottis or on oral pressure, suggesting a common linkage in terms of expiratory effort. When control of glottal opening is attempted in isolation, performance is poor, at least without extensive training. It is not known whether this limitation on laryngeal control is a biologically basic phenomenon. Possibly it is due to the fact that very fine control of glottal opening size may not be necessary for either speech or respiratory phenomena, and hence subjects have no extensive experience with this task.

There is a rich supply of different types of sensory receptors in the larynx [Wyke, 1967, 1974a], and information from such receptors is apparently used in the autonomous control of respiratory phenomena and has also been suggested for phonation [Wyke, 1974b]. Some support in favor of this notion can be invoked from studies of phonation during anesthetization of the laryngeal mucosa or sensory laryngeal nerves [Gould and Okamura, 1974; Gould and Tanabe, 1975; Mallard et al., 1978; Leonard and Ringel, 1979; Sorensen et al., 1980]. The results of these studies generally show small changes in airflow, vocal jitter, or in subjects' ability to follow frequency-modulated tones as a consequence of the anesthesia. However, these studies deal exclusively with phonation, and it is not clear whether similar results would be obtained for control of laryngeal articulatory movements. Although proprioceptive information about glottal opening is undoubtedly available, the present experiments indicate that it cannot be used for voluntary control of glottal aperture. Moreover, the specific role of proprioception in movement perception and control is currently under debate [Kelso et al., 1980].

From a biological point of view, control of glottal opening seldom occurs in isolation, but normally as an integrated part of other activities such as respiration, swallowing, protective reflexes and speech. In speech production, glottal opening is always controlled relative to supraglottal events. On the other hand, control of glottal opening in speech and respiration may be quantal in the sense that the aerodynamic and acoustic consequences of small variations in glottal aperture within a given range are minimal. For speech, calculations presented by Stevens [1971] indicate that when glottal opening is larger than the oral constriction in obstruent production, the sound level of the radiated noise depends on the size of the oral constriction, and variations in glottal aperture produce negligible changes. In fact, for a given range of glottal openings and oral constrictions, the radiated sound level is rather insensitive to variations in both of them. Given that the learning of a language involves mastering of articulatory-perceptual relationships, variations in glottal aperture within a given range would not produce different acoustic and perceptual signals. This fact would then rationalize why glottal opening size alone does not appear to be used to distinguish between otherwise identical sounds except for those differing along the voicing dimension. Variations in the timing of glottal abduction/adduction relative to oral articulations in voiceless obstruent production do, however, produce different acoustic signals and in this respect differ from the control of glottal aperture size. The acoustic and perceptual consequences of variations in interarticulator timing in obstruent production are complex, spread out over a period of time, and involve changes in the sound source and the spectral composition of the signal.

In summary, the present results indicate a rather poor control of glottal aperture even with visual feedback of glottal opening. It is likely that this finding reflects the integrated function of laryngeal abduction adduction. Control of glottal aperture normally occurs as an integral part of respiration or speech production. From a phonetic point of view, glottal aperture itself is apparently not used independently to signal phonological contrasts. In speech, glottal opening and closing always occur relative to supralaryngeal events, and variations in interarticulator timing are commonly used for phonological purposes.

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