Vocal and Neural Responses to Unexpected Changes in Voice Pitch Auditory Feedback During Register Transitions

Sona Patel, Anjli Lodhavia, Saul Frankford, Oleg Korzyukov, and Charles R. Larson, *Evanston, Illinois*

Summary: Objective/Hypothesis. It is known that singers are able to control their voice to maintain a relatively constant vocal quality while transitioning between vocal registers; however, the neural mechanisms underlying this effect are not understood. It was hypothesized that greater attention to the acoustical feedback of the voice and increased control of the vocal musculature during register transitions compared with singing within a register would be represented as neurological differences in event-related potentials.

Study Design/Methods. Nine singers sang musical notes at the high end of the modal register (the boundary between the modal and the head/falsetto registers) and at the low end (the boundary between the modal and the fry/pulse registers). While singing, the pitch of the voice auditory feedback was unexpectedly shifted either into the adjacent register ("toward" the register boundary) or within the modal register ("away from" the boundary). Singers were instructed to maintain a constant pitch and ignore any changes to their voice feedback.

Results. Vocal response latencies and magnitude of the accompanying N1 and P2 event-related potentials were greatest at the lower (modal-to-fry) boundary when the pitch shift carried the subjects' voices into the fry register as opposed to remaining within the modal register.

Conclusions. These findings suggest that when a singer lowers the pitch of his or her voice such that it enters the fry register from the modal register, there is increased sensory-motor control of the voice, reflected as increased magnitude of the neural potentials to help minimize qualitative changes in the voice.

Key Words: Voice–Pitch shift–Register–EEG–ERPs.

INTRODUCTION

The issue of vocal registers has been of interest to singers for hundreds of years, but only in the last several decades has substantial progress been made in understanding how registers are produced. Registers are sections of the vocal pitch range that involve different laryngeal, and possibly supra-laryngeal, settings. Changes in the way the sound is produced typically result in perceivable differences in vocal quality in addition to differences in the voice pitch. Because the sound quality differs between registers, it is important for the singer to make the transition from one register to another smoothly and without an abrupt change in frequency or in quality. Although the number of registers is debated, and the names given to each register differ according to language and musical background, most people agree that there are at least four distinct registers.[1] The lowest register in terms of pitch can be called "vocal fry" (pulse). The register immediately higher than vocal fry can be called the modal or the chest register. Above the modal register is the falsetto (males) or the head (females) register, and the highest is the whistle register. The interest in registers stems in part from the need for highly trained singers to be able to make smooth transitions from one register or mode of vocal fold vibration to another without a break or discontinuity at the register boundaries. Such a smooth transition is in contrast to the "yodel" or the abrupt transitions made by juvenile, nontrained males as they raise the pitch of their voice above the modal range.

With the advent of high-speed vocal fold imaging during vocalization, it has been demonstrated that changes in registers are accompanied by changes in the apparent dimensions of the vocal tract, vocal fold biomechanical properties, and the vocal folds' open quotient.[2–10] Controlling these factors appears to be due, at least in part, to changes in various intrinsic laryngeal muscles.[1,11] More recently, Kochis-Jennings et al[12] provided evidence that precise control of the laryngeal musculature is a prerequisite for the control of voice registers. Thus, increased precision in the control of laryngeal muscles is necessary when a singer is changing voice fundamental frequency (F0) across a register boundary to reduce accompanying changes in voice quality. Indeed, formal singing requires years of practice to learn how to control the laryngeal muscles and possibly other muscles of the vocal tract to make register transitions smooth, that is, without a sudden change in vocal quality.

The present study was designed to investigate neural mechanisms that may be involved in controlling the voice during register transitions using electroencephalography (EEG) combined with the voice pitch-perturbation technique. Studies using this technique have shown that when subjects hear their voice pitch feedback shift up or down while phonating, they respond by changing their voice F0 in the opposite direction to the direction of the pitch shift.[13–15] These vocal responses are automatic and reflect neural mechanisms that are involved in controlling voice F0 at a desired level.[14] We used this technique to elicit vocal and neural responses from singers as they were maintaining a

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Current addresses: [1]Department of Speech-Language Pathology, Seton Hall University, South Orange, New Jersey; [2]Minneapolis VA Health Care System, Minneapolis, Minnesota; [3]Department of Speech, Language & Hearing Sciences, Boston University, Boston, Massachusetts; [4]Meadowlands Hospital Medical Center, Secaucus, New Jersey.

From the Department of Communication Sciences and Disorders, Northwestern University, Evanston, Illinois.

Address correspondence and reprint requests to Charles R. Larson, 2240 Campus Dr., Department of Communication Sciences and Disorders, Northwestern University, Evanston, Illinois 60208. E-mail: clarson@northwestern.edu

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musical note close to the boundary of two adjacent musical registers. Our goal was to determine if singers would respond to the pitch-shift stimuli differently depending on the direction of the pitch shift and the proximity of a register boundary. We anticipated that when the singers heard their voice suddenly transition into an adjacent register, as if it had happened accidentally, they would respond automatically by changing their voice F0 to correct for this unanticipated change and to adjust their voice F0 in a direction away from the register boundary. We also anticipated that a shift directed away from the register boundary would trigger a vocal response, but the vocal response would be smaller than if the pitch shift was directed toward the register boundary. That is, a shift toward the register boundary would require increased attention to the voice acoustical feedback for the control of precise changes in the differential contraction of laryngeal muscles to avoid a change in voice quality. A pitch shift directed away from the boundary would not lead to a change in voice quality and would therefore not require the same degree of differential laryngeal muscle contraction to avoid a change in vocal quality.

We hypothesized that a shift toward (crossing) a register boundary would be perceived by the singer as a change in voice F0 that required changes in neural activation of laryngeal muscles that are important for controlling voice F0 and quality.[12] A pitch shift in the direction away from the register boundary would not be accompanied by a change in voice quality and would therefore not require the same types of changes in laryngeal muscles. Therefore, the differences in acoustical feedback of voice quality or in control of laryngeal muscles should be reflected by differences in cortically recorded event-related potentials (ERPs). While the subjects were performing these vocal tasks, we simultaneously recorded ERPs (triggered by pitch-shift stimuli) from EEG electrodes. Thus, we anticipated that in singers, the vocal responses and ERPs triggered by pitch shifts toward the register boundary would be different from the vocal and the neural responses triggered by pitch shifts away from the register boundary (ie, within the modal register). Hence, the activation or inactivation of the neural networks controlling the voice F0 near a register boundary should be reflected by differences in the magnitudes or timing of ERPs triggered by the pitch-shift stimulus. In addition, the duration of the pitch-shift stimuli used in this study was 200 ms because durations of this length are known to trigger reflexive vocal compensatory mechanisms, whereas longer stimulus durations are likely to provoke voluntary adjustments.[14] Although it is possible for 200-ms pitch-shift stimuli to elicit voluntary changes in voice F0, such changes are variable, unpredictable, and not highly correlated with the direction of the pitch-shift stimuli.[13] Thus, our goal was to investigate possible automatic mechanisms that may be involved in the control of voice F0 across a register boundary.

METHODS

Subjects

Subjects for this study were recruited from the Bienen School of Music, Northwestern University. Subjects were also recruited through the Northwestern A Cappella Community Alliance and *via* social media. Seventeen subjects were tested. Eight subjects were dropped as a result of equipment failure (EEG signals not recorded), resulting in a total of nine subjects who were used in the data analysis. Six of the subjects were female and three were male. Ages of participants in this study ranged from 18 to 24 years. Participants were required to have five or more years of singing experience, have 1 year of formal voice training, sing regularly in a group, and have normal hearing. All participants met these criteria. Participants had normal hearing at the time of testing (passed a bilateral pure-tone hearing screening test at 20-dB sound pressure level at octave intervals from 250 Hz to 4 kHz), had at least 8 years of singing experience (in a choir, in an a cappella group, solo, etc), had at least 1 year of formal voice training (vocal coach, one-on-one sessions), and singing on (at least) a weekly basis at time of study. All but one subject had instrumental musical experience (ie, piano lessons, violin proficiency). Collectively, the participants had a wide array of vocal ranges and categorized themselves as soprano, mezzo-soprano, alto, tenor, baritone, and bass. All subjects reported no history of voice or speech disorders.

Procedures

The study was divided into two parts. The first part was a vocal range and register range evaluation. Participants were given 5 minutes to either warm up on their own or warm up with the assistance of a piano. With the help of an assistant (also musically trained), the frequency range of each participant's register break (from chest/normal voice to head/falsetto, and from chest/normal voice to vocal fry) was noted. Then, the subject was instructed to sing as high as possible in the chest/normal vocal range and as low as possible in the same register. The participant's voice was recorded at his or her lowest and highest note in the chest/modal range during the production of a prolonged /a/ vowel sound ("ahh") lasting approximately 3 seconds.

The second part of the study was the main experiment. For this portion of the test, an EEG electrode cap was first attached to the subject's head (Easycap GmbH, Herrsching, Germany). Thirty-two electrode sites were cleaned, and conductance gel was applied to each site, including the left and the right mastoids, in accordance with the extended international 10–20 system.[16] Electrode impedances were kept below 5 kΩ for all channels. The electrooculogram signals were recorded using two pairs of bipolar electrodes, one pair placed above and below the right eye to monitor vertical eye movements, and the other pair placed at the canthus of each eye to monitor horizontal eye movements. During analysis of the EEG signals, the amplifier automatically rejected trials when electrical potentials related to eye movements caused abnormally large potentials from the EEG electrodes. Scalp-recorded brain potentials were low-pass filtered with a 400-Hz cutoff frequency (anti-aliasing filter), digitized at 2 kHz, and recorded using a BrainVision QuickAmp amplifier (Brain Products GmbH, Gilching, Germany).

Following application of the electrodes, participants were seated in a sound-treated booth. A microphone (AKG boomset microphone, model C420, Vienna, Austria) was placed 1 inch in front of the mouth, and Etymotic earphones (model ER1-14A, Elk