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Vocal and neural responses to unexpected changes in voice pitch auditory feedback during register transitions

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Abstract

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 to singing within a register would be represented as neurological differences in event-related potentials (ERPs).

Study Design/Methods—Nine singers sang musical notes at the high end of the modal register (the boundary between the modal and head/falsetto registers) and at the low end (the boundary between the modal and 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 ERPs were greatest at the lower (modal-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 their 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.

Keywords

Voice; pitch-shift; register; EEG; ERPs

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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 supralaryngeal, 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. Since 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 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 (Sundberg 1987). 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 chest register. Above the modal register is the falsetto (males) or 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, non-trained 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 (Sonninen et al. 1999, Miller et al. 2002, Henrich et al. 2005, Echternach et al. 2008, Echternach et al. 2010, Echternach et al. 2011, Echternach et al. 2011, Zanartu et al. 2011, Echternach et al. 2014). Controlling these factors appears to be due, at least in part, to changes in various intrinsic laryngeal muscles (Hirano et al. 1970, Sundberg 1987). More recently Kochis-Jennings (Kochis-Jennings et al. 2014) 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 F0 across a register boundary in order 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 in order to make register transitions smooth, i.e., 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 fundamental frequency (F0) in the opposite direction to the direction of the pitch-shift (Burnett et al. 1998, Hain et al. 2000, Behroozmand et al. 2012). These vocal responses are automatic and reflect neural mechanisms that are involved in controlling voice F0 at a desired level (Hain et al. 2000). We used this technique to elicit vocal and neural responses from singers as they were maintaining a 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 towards the register boundary. That is, a shift towards 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 in order 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 towards (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 (Kochis-Jennings et al. 2014). 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 towards the register boundary would be different from the vocal and neural responses triggered by pitch shifts away from the register boundary (i.e., 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 (Hain et al. 2000). 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 (Burnett et al. 1998). 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 (NACCA) 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 18-24 years. Participants were required to have five or more years of singing experience, have one 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 eight years of singing experience (in choir, in an a cappella group, solo, etc.), had at least one year of formal voice training (vocal coach, 1-1 sessions), and sing on (at least) a weekly basis at time of study. All but one subject had instrumental musical experience (i.e. piano lessons, violin proficiency, etc.). 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 five 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/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, Germany). Thirty-two electrode sites were cleaned, and conductance gel was applied to each site, including the left and right mastoids, in accordance with the extended international 10-20 system (Burkard et al. 2006). Electrode impedances were kept below 5 k Ω for all channels. The electrooculogram (EOG) signals were recorded using two pairs of bipolar electrodes placed above and below the right eye to monitor vertical eye movements and 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 cut-off frequency (anti-aliasing filter), digitized at 2 kHz, and recorded using a BrainVision QuickAmp amplifier (Brain Products GmbH, Germany).

Following application of the electrodes, participants were seated in a sound-treated booth. A microphone (AKG boomset microphone, model C420) was placed one inch in front of the mouth, and Etymotic earphones (model ER1-14A) were inserted into the ear canals. Subjects' voices were picked up from the microphone, amplified with a Mackie mixer (model 1202-VLZ3), pitch-shifted through an Eventide Eclipse Harmonizer, and then presented to the subject's earphones such that the subject heard his/her voice feedback over earphones in real-time. Voice and auditory feedback were sampled at 10 kHz using PowerLab A/D Converter (Model ML880, AD Instruments) and recorded onto a laboratory

computer with Chart software (AD Instruments). The feedback signal (i.e., the participant's pitch-shifted voice) was presented at about 80-85 dB. The 10 dB gain in the feedback channel relative to vocal output (controlled by a Crown amplifier D75) was used to partially mask airborne and bone-conducted voice feedback.

Prior to each vocalization the subject heard one of his/her pre-recorded voice samples (lowest or highest note in the modal register) and was instructed to vocalize at that pitch level for the ensuing vocalization. During the vocalizations the subject's voice was randomly shifted upwards or downwards by 400 cents, causing the subject to perceive the voice cross the register boundary ("toward the register boundary", i.e., a downward shift at the low register or an upward shift at the high register) or to remain within the modal register ("away from the register boundary"). Although most studies using the pitch-shift paradigm use smaller magnitude pitch shifts (Burnett et al. 1998, Hain et al. 2000, Liu and Larson 2007, Behroozmand et al. 2012), we considered it necessary to use a larger stimulus in this study to make sure the subject's perceived F0 crossed a register boundary. Each shift began randomly between 500 and 700 ms after vocal onset and lasted for 200 ms. The pitch-shift onset times, indicated by transistor-transistor logic (TTL) pulses, were recorded along with the audio signals on the PowerLab system. Subjects vocalized 50 times during each of four blocks of trials. Fig. 1 shows a schematic illustration of the experiment in which subjects vocalized close to either the high or low register boundary, after which their voice auditory feedback was shifted either towards or away from the register boundary. In the illustration only stimuli shifting the auditory feedback towards the register boundary are shown.

Data Analysis

Voice analysis

For voice data analysis, the voice and feedback signals were first processed in Praat (Boersma, 2001) to obtain the F0 contours. Then the F0 contours along with TTL pulses corresponding to the stimulus onset and magnitude were processed in IGOR PRO (Wavemetrics, Lake Oswego, OR) data analysis software for computation of averaged F0 contours. The vocal F0 responses to the pitch shifts were averaged across an 850 ms window (from 200 ms before the shift to 650 ms after the shift) for each individual participant, stimulus direction, and register level. Then these responses were grand-averaged across participants (Fig. 2). The averaging program calculated the pre-stimulus F0 level as well as the peak magnitude and time of peak magnitude of the averaged F0 response for each subject and condition. For F0 magnitude measures the F0 values were first referenced to the pre-stimulus level, which was set to 0, and then the absolute value of the response magnitudes was used to avoid averaging positive and negative values (only compensatory responses were analyzed, about 80% of trials). Changes in dependent variables or DVs (peak time, peak magnitude) were evaluated using two-way repeated measures analysis of variance (ANOVA) using SPSS (IBM SPSS Statistics, v.22) and DataDesk software. First, RMANOVAs were performed to identify differences in the DVs due to shift direction at each register boundary. We were primarily interested in the differences in shift direction at each register boundary in order to determine if there were any changes due to pitch shifts *within* a

register compared to shifts *between* registers and whether any observed changes varied depending on the registers involved (fry-modal vs modal-head/falsetto).

EEG analysis

EEG recordings were referenced to the average reference montage, in which the outputs of all amplifiers are averaged and used as the common reference. After recording a block of trials, the EEG signals were filtered offline using a band-pass filter with cut-off frequencies set to 1 Hz and 50 Hz (48 dB/oct) and then segmented into epochs ranging from 100 ms before and 400 ms after the onset of the pitch shift stimuli. Epochs with EEG or EOG amplitudes exceeding 75 μ V were removed from data analysis. At least 80 epochs for the two different register conditions and the different stimulus directions were averaged for ERP calculation for all participants.

Initial analysis of the ERP topographic maps showed that the frontal and central electrodes (F3, Fz, F4, FC3, FCz, FC4 C3, Cz, C4) had the largest positive and negative amplitudes in response to the pitch-shift stimuli. From the ERPs for each subject, the peak amplitudes in the N1 ERP (time and amplitude of the most negative potential occurring between 80 and 120 ms after the stimulus) and P2 (time and magnitude of the most positive potential occurring between 150 and 250 ms after the stimulus) were computed for these nine electrode sites. The N1 and P2 potentials have been shown in previous studies to be sensitive to pitch-shifted voice auditory feedback (Behroozmand et al. 2009, Hawco et al. 2009, Scheerer et al. 2013). The N1 and P2 peak amplitude data (DVs) were collapsed across individual electrode sites, and the combined data from the nine electrode sites were submitted to statistical testing because preliminary analysis suggested that the stimuli elicited differences in peak magnitudes of these potentials. Our independent variables were register boundary (low, high) and shift direction (toward, away from register boundary). As with the voice analysis, RM-ANOVAs were used to identify differences in voice response *peak time* and *peak magnitude* due to shift direction and register boundary. We were primarily interested in the differences in shift direction at each register boundary to determine changes due to pitch shifts *within* vs between registers and whether these changes varied based on the register boundary (high vs low), which were assessed using paired samples t-tests.

Results

Voice Measures

Figure 2 displays the grand average voice F0 responses to downward and upward pitch-shift stimuli for the high and low registers. For the downward stimuli in the high register, subjects produced an increase in voice F0 that had a peak magnitude of 27.48 cents, and for up stimuli in the high register, the mean downward response magnitude (absolute magnitude) was 26.69 cents. For the low register, down stimuli led to a mean response magnitude of 29.35 cents, while up stimuli produced a mean (absolute) response magnitude of 33.79 cents. For analysis of response magnitudes, a two (shift direction) by two (register boundary) RM-ANOVA showed non-significant main effects for stimulus direction ($F(1,8) = .719$, $p >$

0.05), register boundary ($F(1,8) = 1.14, p > 0.05$), and a direction by register interaction ($F(1,8) = 1.94, p > 0.05$).

For the timing of the responses in the low register, downward responses had peak times of 333 ms, while upward responses peaked at 266 ms. For the high register downward response, peak times were 245 ms, and upward responses were 189 ms. A two (shift direction) by two (register boundary) RM-ANOVA showed a non-significant effect for shift direction ($F(1,8) = 2.09, p > 0.05$) and a non-significant interaction for register boundary by direction ($F(1,8) = 0.55, p > 0.05$). However, the time of the peak was significantly different as a function of the register boundary ($F(1,8) = 10.73, p < 0.05$). Thus, although the magnitude of the vocal responses did not differ whether subjects received upwards or downwards stimuli at the high or low registers, responses were faster in the high register compared to the low register.

EEG Measures

RM-ANOVAs were used to test for significant differences for ERP potentials N1 and P2 in stimulus direction (up, down), register boundary (high, low), and the interaction between direction and register boundary. For the N1 potential magnitude, there were significant main effects for register boundary ($F(1,80) = 25.5, p < 0.0001$), and stimulus direction ($F(1,80) = 50.57, p < 0.0001$). We report the 2-way interaction of stimulus direction by register boundary here, ($F(1,80) = 3.74, p > 0.05$), however, because we were interested in differences at *either* the high register or low register, we tested the stimulus direction by register boundary interaction using paired samples t-tests. Results indicated a significant difference in the N1 potential magnitude between downward compared to upward responses at the low register (Fz: $t = -2.245, p = 0.055$, FCz: $t = -3.484, p < 0.05$; Cz: $t = -2.695, p < 0.05$) but not downward compared to upward responses at the high register (Fz: $t = -1.708, p > 0.05$; FCz: $t = -0.542, p > 0.05$; Cz: $t = -1.525, p > 0.05$). In addition, mean N1 amplitudes across the three electrodes were significantly larger for the low register ($-2.91 \mu V$) than the high register ($-1.74 \mu V$; $t = -4.691, p < 0.05$). Thus, the non-significant interaction term is potentially due to the non-significant differences in upward vs downward stimuli at the high register. Together, these results indicate that the N1 ERP magnitudes in the low register were different for shifts that were toward vs away from the register boundary.

Similar tests were performed on the P2 amplitude. Results revealed significant effects for stimulus direction ($F(1,80) = 105.59, p < 0.0001$) and register boundary ($F(1,80) = 30.02, p < 0.0001$). Once again we report the 2-way interaction of stimulus direction by register boundary ($F(1,80) = 0.03, p > 0.05$), which was not significant. However, paired samples t-tests revealed significant differences between downward responses compared to upward responses on two of the three electrodes at the low register (Fz: $t = 2.426, p < 0.05$, FCz: $t = 3.107, p < 0.05$) and at the high register (Fz: $t = 3.107, p < 0.05$; FCz: $t = 2.853, p < 0.05$; Cz: $t = 1.656, p > 0.05$). These results show that like the N1 response, P2 ERP amplitude changes in the neural processing mechanisms were observed when the stimulus crossed the lower register boundary, but in this case, also the upper register boundary.

Fig. 3 illustrates the grand averaged ERPs for three electrodes, Fz, FCz and Cz in the low register vocal condition. The blue lines indicate average ERPs with downward stimuli

(towards the low register or “within the modal register”) while the red lines show responses to upward stimuli (away from the low register or “across registers”). Fig. 4 shows similar data for ERP responses at the high register boundary. In this figure the blue line shows ERPs in response to upward stimuli (towards the higher register or “across registers”) while the red line shows ERPs in response to downward stimuli (away from the higher register or “within the modal register”).

Discussion

The present study was an attempt to determine if it is possible to identify neural mechanisms that are related to the control of voice during register transitions. The literature on vocal registers abounds with descriptions of peripheral mechanisms and perceptual identification of registers (Roubeau et al. 1987, Abramson et al. 2004, Henrich 2006, Echternach et al. 2008, Salomao and Sundberg 2008, Echternach et al. 2010, Echternach et al. 2011, Echternach et al. 2011, Echternach et al. 2012, Echternach et al. 2014), but we were unable to locate sources in the literature that were related to brain mechanisms involved during register transitions. Here we report the vocal and neural responses (ERP) produced by changes in voice pitch auditory feedback that sounded to the subject as though their voice F0 was suddenly and unintentionally changing either from their modal register into another register (fry or head, referred to as “towards the register boundary”) or to a different pitch level within their modal register (referred to as “away from the register boundary”). We reasoned that pitch shifts towards the register boundary would trigger learned responses and corresponding neural mechanisms that prevent singers from producing a dramatic change in voice quality as their voice F0 transitions into an adjacent register. One explanation for the faster voice F0 responses to downward pitch shift stimuli at the high register compared to the low register is that singers more typically sing musical notes near the higher end of their range (near the upper register) than the lower end and hence have more experience in adjusting their voice register control at the higher register compared to the lower register.

As for the results of the ERP analysis, both the N1 and P2 potentials reflect widespread cortical processing of many different mechanisms. The N1, which may be related to the mismatch negativity potential (Hawco et al. 2009), is probably involved at an earlier stage of processing of voice auditory feedback, while the P2 is probably involved in more complex processing of sensory feedback for motor (voice) control. We report that N1 ERPs from frontal regions of the head were larger in magnitude for shifts toward the lower register compared to shifts toward the high register boundary. The precise reasons for the increase in the N1 ERP are difficult to ascertain since the N1 has shown to be enhanced to a number of different factors such as a rapid response to a stimulus (Korzyukov et al. 2012, Korzyukov et al. 2012), a change in the acoustical feedback signal (Hawco et al. 2009) stimulus unpredictability (Korzyukov et al. 2012), complexity of the voice auditory feedback signal (Behroozmand et al. 2012), and the significance of the auditory feedback signal during vocalization (Behroozmand et al. 2014). In agreement with previous studies (Liu et al. 2011, Behroozmand et al. 2014), the N1 potential was also larger in response to downward shifts in voice auditory feedback compared to upward shifts. Finally, the N1 potential serves as a marker for self-generated vocalizations compared to non-self vocalizations (Houde et al. 2002, Behroozmand and Larson 2011, Behroozmand et al. 2011). Of these various factors,

the observation that it is common for the N1 to be enhanced for downward compared to upward shifts in voice auditory feedback may explain the results of this study, however the specific neural reasons for this are unknown.

Previous studies using the pitch-shifting technique with EEG recording have also reported changes in the P2 ERP, which may help explain the significant changes in the P2 ERP with stimulus direction and register boundary. The P2 ERP has been shown to be more sensitive to voice auditory feedback during vocalization and auditory feedback than to auditory feedback alone (Behroozmand et al. 2009), or to auditory feedback during a general motor task (Liu et al. 2010). The P2 sensitivity was also enhanced when the feedback signal was the same as or very similar to the vocal production (Behroozmand et al. 2011). These observations suggest the P2 reflects a more advanced stage of cortical processing of auditory feedback during vocalization than the N1 potential. These processes could be generally related to the relevance to sensory feedback for motor control.

Further details on possible neural changes related to the shifts that crossed register boundaries may be garnered from a study on formant-shifting. In a study by Niziolek and colleagues (Niziolek et al. 2013), speech formants were shifted across vowel categories. The salience of the closeness of the vowel boundary to the vowel preceding the shift led to enhanced neural processing in the right posterior temporal gyrus. That is, the closer the vowel being produced was to a vowel boundary, the greater the neural activation. In the context of the present study, the enhanced N1 and P2 responses to the pitch-shifts across the register boundary may reflect similar, although non phonetic, mechanisms of motor control. Further studies focused on more specific features of the vocalizations and auditory feedback under singing conditions would be necessary to fully explain the ERP results of this study.

There are several reports on changes in vocal fold vibratory patterns associated with different vocal registers such as the open quotient, formant frequencies, and laryngeal EMG (Sundberg 1987, Miller et al. 2002, Henrich et al. 2005, Echternach et al. 2008, Echternach et al. 2010, Echternach et al. 2011, Echternach et al. 2011, Zanartu et al. 2011, Echternach et al. 2014). Although it is not known for certain how changes in laryngeal muscle contraction affects vocal fold vibrations corresponding to changes in the open quotient, it may be assumed that the control of vocal fold vibrations relates either to myoelastic properties of the vocal folds or aerodynamics (Myoelastic aerodynamic theory of voice production) (Titze 1980), or to both. Furthermore, control of vocal fold mechanical properties must relate to laryngeal muscles, while aerodynamics could relate to laryngeal, respiratory or upper vocal tract musculature. Since all these muscles are controlled by the central nervous system, any change in the CNS related to changes in vocal tract muscles, should in theory be detectable using conventional methods of brain function measurement such as EEG.

Although we noted that significant changes in ERPs were observed when the pitch shifted feedback was shifted towards either the upper or lower register boundaries, the magnitudes of the ERPs were clearly larger at the lower compared to the upper register. The reasons for this disparity may be due to the fact that it was more difficult for both the singers and experimenter to detect a difference in vocal quality at the register boundary between chest and head registers in the group of subjects tested. This may be because it was more difficult

to perceptually identify this boundary, and the singers may have been able to make this transition smoothly across a broader range of frequencies than was possible with the chest to pulse register. Because of this difficulty the musical notes selected for the upper boundary condition may not have been uniform across the subjects. The note chosen may have been closer to their optimal transition frequency in some subjects and further away in other subjects. This could be due to differences in a person's vocal range. In addition to including some variability in register boundaries by not controlling for vocal range, a larger vocal range could influence the response to a pitch-shift near a register boundary simply because singers with larger ranges would have register boundaries that are further apart. It is possible that more consistency could be achieved by including individuals of a specific vocal quality (e.g., sopranos, altos, tenors, etc.). Tenors and sopranos would likely respond to the modal-head register boundary differently than altos and basses because of the amount of time spent crossing the register boundary during professional vocalization (i.e., tenors and sopranos spend more time crossing the higher register boundary than the lower, while altos and basses spend more time near the low end of their modal register). Additional studies wherein the register boundaries are more carefully defined and uniform across all subjects may lead to clearer results than we were able to obtain.

A question that may arise from consideration of the technique used in this experiment may be why we did not attempt to record ERPs when subjects were volitionally changing their voice F0 from one register to another? Such a technique is certainly possible, but it would also invoke other cognitive mechanisms that may not relate directly to control of laryngeal, respiratory, or upper airway muscles. Also, ERPs are most sensitive to sudden changes in neural activity rather than gradual changes in neural activity that might occur as a singer is volitionally changing voice F0 from one pitch to another. Hence we developed a technique in which it would sound to the vocalist as if the voice were suddenly changing in pitch “accidentally” and needed to be corrected immediately.

The technique used in this study suggests that there was a difference in the way singers corrected for a voice auditory feedback signal that sounded like a pitch error within the intended register compared to an error that crossed from one register to another. The differences in the ERPs in these two conditions represent complex neural processing that may include perceptual mechanisms related to the change in voice auditory feedback and motor mechanisms related to changes in contraction of laryngeal muscles. Unfortunately, ERPs recorded from scalp electrodes do not provide information on the exact neural mechanisms or the brain locations where these activities occurred.

Conclusion

In the present study it was demonstrated that when voice auditory feedback of singers holding a musical note is suddenly shifted in pitch such that the perceived pitch either crosses the boundary between the modal and fry or the modal and head register or stays within the modal register, there is a change both in the vocal and EEG response to the shift. Moreover, the magnitude of the vocal and EEG responses were greatest when the perceived pitch suddenly entered the fry register compared to entering the head register or staying within the modal register. These results suggest that the singers adjust to the sudden shift

into the fry register by activating neural mechanisms that may diminish the magnitude of a qualitative change in the voice. The technique employed in this study may be useful in future studies on neural mechanisms of voice control during singing.

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References

- Abramson AS, T LT, Nye PW. Voice register in Suai (Kuai): an analysis of perceptual and acoustic data. *Phonetica*. 2004; 61(2-3):147–171. [PubMed: 15662109]
- Behroozmand R, Ibrahim N, Korzyukov O, Robin DA, Larson CR. Left-hemisphere activation is associated with enhanced vocal pitch error detection in musicians with absolute pitch. *Brain Cogn*. 2014; 84(1):97–108. [PubMed: 24355545]
- Behroozmand R, Karvelis L, Liu H, Larson CR. Vocalization-induced enhancement of the auditory cortex responsiveness during voice F0 feedback perturbation. *Clin Neurophysiol*. 2009; 120(7): 1303–1312. [PubMed: 19520602]
- Behroozmand R, Korzyukov O, Larson CR. Effects of voice harmonic complexity on ERP responses to pitch-shifted auditory feedback. *Clin Neurophysiol*. 2011; 122(12):2408–2417. [PubMed: 21719346]
- Behroozmand R, Korzyukov O, Larson CR. ERP correlates of pitch error detection in complex tone and voice auditory feedback with missing fundamental. *Brain Res*. 2012; 1448:89–100. [PubMed: 22386045]
- Behroozmand R, Korzyukov O, Sattler L, Larson CR. Opposing and following vocal responses to pitch-shifted auditory feedback: evidence for different mechanisms of voice pitch control. *J Acoust Soc Am*. 2012; 132(4):2468–2477. [PubMed: 23039441]
- Behroozmand R, Larson CR. Error-dependent modulation of speech-induced auditory suppression for pitch-shifted voice feedback. *BMC Neurosci*. 2011; 12:54. [PubMed: 21645406]
- Behroozmand R, Liu H, Larson CR. Time-dependent neural processing of auditory feedback during voice pitch error detection. *J Cogn Neurosci*. 2011; 23(5):1205–1217. [PubMed: 20146608]
- Burkard, R.; Don, M.; Eggermont, J., editors. Auditory evoked potentials: Basic principles and clinical application. Lippincott Williams & Wilkins; Philadelphia, PA: 2006.
- Burnett TA, Freedland MB, Larson CR, Hain TC. Voice F0 Responses to Manipulations in Pitch Feedback. *J. Acoust. Soc. Am*. 1998; 103(6):3153–3161. [PubMed: 9637026]
- Echternach M, Dippold S, Richter B. High-speed imaging using rigid laryngoscopy for the analysis of register transitions in professional operatic tenors. *Logoped Phoniater Vocol*. 2014:1–8. [PubMed: 25017997]
- Echternach M, Dippold S, Sundberg J, Arndt S, Zander MF, Richter B. High-speed imaging and electroglottography measurements of the open quotient in untrained male voices' register transitions. *J Voice*. 2010; 24(6):644–650. [PubMed: 20083378]
- Echternach M, Sundberg J, Arndt S, Breyer T, Markl M, Schumacher M, Richter B. Vocal tract and register changes analysed by real-time MRI in male professional singers-a pilot study. *Logoped Phoniater Vocol*. 2008; 33(2):67–73. [PubMed: 18569645]
- Echternach M, Sundberg J, Zander MF, Richter B. Perturbation measurements in untrained male voices' transitions from modal to falsetto register. *J Voice*. 2011; 25(6):663–669. [PubMed: 20488660]
- Echternach M, Traser L, Markl M, Richter B. Vocal tract configurations in male alto register functions. *J Voice*. 2011; 25(6):670–677. [PubMed: 21402469]
- Echternach M, Traser L, Richter B. Perturbation of voice signals in register transitions on sustained frequency in professional tenors. *J Voice*. 2012; 26(5):674, e679–615. [PubMed: 22633333]

- Hain TC, Burnett TA, Kiran S, Larson CR, Singh S, Kenney MK. Instructing subjects to make a voluntary response reveals the presence of two components to the audio-vocal reflex. *Experimental Brain Research*. 2000; 130:133–141. [PubMed: 10672466]
- Hawco CS, Jones JA, Ferretti TR, Keough D. ERP correlates of online monitoring of auditory feedback during vocalization. *Psychophysiology*. 2009
- Henrich N. Mirroring the voice from Garcia to the present day: some insights into singing voice registers. *Logoped Phoniatr Vocol*. 2006; 31(1):3–14. [PubMed: 16531287]
- Henrich N, D'Alessandro C, Doval B, Castellengo M. Glottal open quotient in singing: measurements and correlation with laryngeal mechanisms, vocal intensity, and fundamental frequency. *J Acoust Soc Am*. 2005; 117(3 Pt 1):1417–1430. [PubMed: 15807029]
- Hirano M, Vennard W, Ohala J. Regulation of register, pitch and intensity of voice. *Folia Phoniatrica Et Logopaedica*. 1970; 22:1–20.
- Houde JF, Nagarajan SS, Sekihara K, Merzenich MM. Modulation of the auditory cortex during speech: An MEG study. *Journal of Cognitive Neuroscience*. 2002; 14(8):1125–1138. [PubMed: 12495520]
- Kochis-Jennings KA, Finnegan EM, Hoffman HT, Jaiswal S, Hull D. Cricothyroid Muscle and Thyroarytenoid Muscle Dominance in Vocal Register Control: Preliminary Results. *J Voice*. 2014
- Korzyukov O, Karvelis L, Behroozmand R, Larson CR. ERP correlates of auditory processing during automatic correction of unexpected perturbations in voice auditory feedback. *Int J Psychophysiol*. 2012; 83(1):71–78. [PubMed: 22044551]
- Korzyukov O, Sattler L, Behroozmand R, Larson CR. Neuronal mechanisms of voice control are affected by implicit expectancy of externally triggered perturbations in auditory feedback. *PLoS One*. 2012; 7(7):e41216. [PubMed: 22815974]
- Liu H, Behroozmand R, Larson CR. Enhanced neural responses to self-triggered voice pitch feedback perturbations. *NeuroReport*. 2010; 21(7):527–531. [PubMed: 20386347]
- Liu H, Larson CR. Effects of perturbation magnitude and voice F0 level on the pitch-shift reflex. *J. Acoust. Soc. Am*. 2007; 122(6):3671–3677. [PubMed: 18247774]
- Liu H, Meshman M, Behroozmand R, Larson CR. Differential effects of perturbation direction and magnitude on the neural processing of voice pitch feedback. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*. 2011; 122(5):951–957. [PubMed: 20869305]
- Miller DG, Svec JG, Schutte HK. Measurement of characteristic leap interval between chest and falsetto registers. *J Voice*. 2002; 16(1):8–19. [PubMed: 12002890]
- Niziolek CA, Nagarajan SS, Houde JF. What does motor efference copy represent? Evidence from speech production. *J Neurosci*. 2013; 33(41):16110–16116. [PubMed: 24107944]
- Roubeau B, Chevie-Muller C, Arabia-Guidet C. Electrolottographic study of the changes of voice registers. *Folia Phoniatr (Basel)*. 1987; 39(6):280–289. [PubMed: 3428796]
- Salomao GL, Sundberg J. Relation between perceived voice register and flow glottogram parameters in males. *J Acoust Soc Am*. 2008; 124(1):546–551. [PubMed: 18646997]
- Scheerer NE, Behich J, Liu H, Jones JA. ERP correlates of the magnitude of pitch errors detected in the human voice. *Neuroscience*. 2013; 240:176–185. [PubMed: 23466810]
- Sonninen A, Hurme P, Laukkanen AM. The external frame function in the control of pitch, register, and singing mode: radiographic observations of a female singer. *J Voice*. 1999; 13(3):319–340. [PubMed: 10498050]
- Sundberg, J. *The Science of the Singing Voice*. Northern Illinois University Press; Dekalb, IL: 1987.
- Titze I. Comments on the myoelastic-aerodynamic theory of phonation. *Journal of Speech and Hearing Research*. 1980; 23:495–510. [PubMed: 7421153]
- Zanartu M, Mehta DD, Ho JC, Wodicka GR, Hillman RE. Observation and analysis of in vivo vocal fold tissue instabilities produced by nonlinear source-filter coupling: a case study. *J Acoust Soc Am*. 2011; 129(1):326–339. [PubMed: 21303014]

Fig. 1. Schematic illustration of the experiment in which subjects vocalized close to the high and low register boundaries

This figure shows the direction of the pitch-shifts toward the low and high register boundaries along with an illustration of the resulting compensatory vocal response relative to the register boundaries. The arrows emphasize the direction of the pitch shift (red indicates the upward shift, and blue indicates the downward shift).

Fig. 2. Grand-averaged voice responses across participants

The grand-averaged vocal responses are shown for the low register (left) and the high register (right). Stimuli towards the register boundary are shown in blue and stimuli away from the register boundary are shown in red. Vertical bars are standard error of the mean.

Fig. 3. Event-related potentials at the low register boundary with corresponding topographical distribution maps

The event-related potentials due to downward (blue lines) and upward (red lines) stimuli are shown for three electrodes (top to bottom: Fz, FCz, Cz) for the N1 potentials (top) and P2 potentials (bottom). The corresponding topographical distribution maps are shown next to each set of figures. Colored vertical bars at 100 and 200 ms indicate time where ERP magnitudes were measured.

Fig. 4. Event-related potentials at the high register boundary with corresponding topographical distribution maps

The event-related potentials due to downward (red lines) and upward (blue lines) stimuli are shown for three electrodes (top to bottom: Fz, FCz, Cz) for the N1 potentials (top) and P2 potentials (bottom). The corresponding topographical distribution maps are shown next to each set of figures.