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Violinists' Perceptions of and Motor Reactions to Fundamental Frequency Shifts Introduced in Auditory Feedback

Honorata Hafke-Dys, Anna Preis, David Trojan
Institute of Acoustics, Adam Mickiewicz University, Umultowska 85, 61-114 Poznan, Poland.
h.hafke@amu.edu.pl

Summary
During vocalization, compensating motor reactions are observed in response to unnoticed changes of voice fundamental frequency. The occurrence of these reactions was investigated with violin playing, by obtaining violinists' perception thresholds and motor reactions to fundamental frequency shifts in auditory feedback. The data shows that the violinists reacted to fundamental frequency perturbation by fully compensating for the change of fundamental frequency. This reaction also occurred for changes, which were determined to be below the perception threshold.

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1. Introduction

Recently there have been many studies on the interaction between the auditory and motor systems. Humans can perceive external sounds, i.e. a car passing by, noisy children etc., but they are also a source of sounds, through vocalization or instrument playing. With external sounds, the auditory system needs to analyze and assign meaning to the sounds, by determining the sound source and its location. On the other hand, the human body is itself a source of sounds that reach the auditory system throughout auditory feedback. Produced sounds are analyzed and a controlling mechanism is applied through appropriate muscle work to produce an expected pitch or volume. Generally speaking, in the case of external sounds the information about the surrounding world is obtained by perception, whereas during sound production it is the human body that influences the surroundings. As a by-product of the latter situation a feedback loop is created, a special kind of "echo", that should be distinguishable to the brain from the external sounds that simultaneously reach the auditory system. This auditory feedback makes it possible to control voice parameters in real time and to maintain the intended pitch during instrument playing. The working of this mechanism can be made visible in an experimental environment, when a modification is introduced to auditory feedback information, and subjects' reactions are observed. A number of studies show the reaction of the auditory-motor system to either fundamental frequency changes, or sound pressure level changes, to both speech sounds and singing [1, 2, 3, 4, 5, 6, 7, 8, 9]. Usually, a compensatory reaction can be observed, with subjects raising either the frequency or sound pressure level of their voice when the frequency or the sound pressure level of the feedback information is artificially lowered. Previous studies [5, 6, 7, 4, 10] showed that these reactions occur even for minor, unobservable changes. Hafke [5] suggested that this could be related to the motor-perception distinction in the auditory domain, similar to the separation that was found in the visual modality [11]. In the case of musical sounds it was found that the presence of auditory feedback is very important in the process of learning a musical piece. Strong reactions to temporal and rhythmical changes were also observed. The studies by Repp [12, 13] showed that even minor, imperceptible changes to a rhythmical sequence were compensated for. It is still debatable, however, if the control of self-generated sound can take place independently of our perception and awareness.

This paper aims to determine how the perception and motor control mechanisms work during violin playing. The main aim of the study is to determine the musicians' motor reactions to frequency perturbations in auditory feedback. The hypothesis tested in this study is that motor reactions observed in response to fundamental frequency (f_0) shifts in auditory feedback occur even without perceiving them. To determine perceptions thresholds for self generated sounds violinists evaluated f_0 changes while playing, subsequently answering a question about the changes (constant stimuli method). The results of perceptual thresholds were compared with the violinists' motor reactions.

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2. Subjects

Eight professional musicians (violinists), 4 males and 4 females, participated in this study. All participants have a higher education degree in music. They reported no neurological defects or disorders. The participants were seated in a sound-treated room. One participant was excluded on the basis of the Alfa Cronbacha index [14]. The main basis for his exclusion was his motor reactions, which were in opposition to those of all other participants. Instead of pitch compensation shown by other subject he exhibited the reaction of following presented frequency changes. Similar cases were noticed in experiments on vocal control of voice fundamental frequency [15]. After his removal, Alpha Cronbacha increased from 0.915 to 0.989.

3. Method

The violinists were asked to play steady notes repeatedly using an electric violin (Yamaha SV 130 CAR). An electric variant of the instrument was chosen as it enabled a separation from the violin corpus sounds, while giving the musicians the same ease of playing. Two frequencies were chosen: 427 Hz (a sound the f_0 of which does not belong to the musical scale) and 1046.5 Hz (C^3 note). The violinists hear only the sound from the pick-up output of the electric violin which was modified in real time during the experiment. Additionally, in order to mask the trace of the direct sound, closed-back headphones were used (Beyerdynamic 150 DT). Finally, the sound pressure level was chosen in such a way that the violinist could only hear the processed sound. At the beginning of each series of repetitions, a sound sample of a given frequency (a pre-recorded 5 s electric violin sound obtained with a single bow stroke with steady dynamics with a frequency 427 or 1046.5 Hz) was presented to the subjects. Violinists were instructed to reproduce the sound they were hearing with a single bow stroke with steady dynamics. A visual stimulus presented on a computer screen informed them of the beginning and the end of the play. Unknowingly to them, a frequency modification was introduced in the third second of playback, using a DP2 Ensoniq ultraharmonizer triggered by MIDI commands. The modifications lasted for the remaining duration of playback. The values of frequency modifications used were 3, 6, 12, 24, 48 cents in both directions and were presented randomly during the session. Zero-pitch-shift condition had also been included in the experiment. Each modification was repeated 20 times for each of the two fundamental frequencies (427 Hz and 1046.5 Hz).

The sound played by the violinists was recorded on a computer using an RME Babyface sound card for later analysis. Each recorded sound sample was analyzed by a dedicated algorithm written in MATLAB in order to check the motor reaction to the f_0 shift introduced in auditory feedback. According to this algorithm, two mean values of the f_0 were calculated using the autocorrelation method: the first one averaged over a 1.5 second duration before the f_0 shift and the second one 1.5 second after the f_0 shift (excluding the reaction time). The difference between these two means was calculated and stored in cents.

In addition, during a 5 second pause between each playing sound, subjects were asked to answer a question: "In which direction did the sound pitch change? Up or down?" The violinists' answers were gathered and used to create psychometric curves and determine perception thresholds.

Table I. Averaged perception threshold values for 427 Hz and 1046.5 Hz sound.

427 Hz (average)	**3.8**
upward f_0 shift (75%)	2
downward f_0 shift (25%)	5.6
1046.5 Hz (average)	**5.1**
upward f_0 shift (75%)	3.8
downward f_0 shift (25%)	6.4

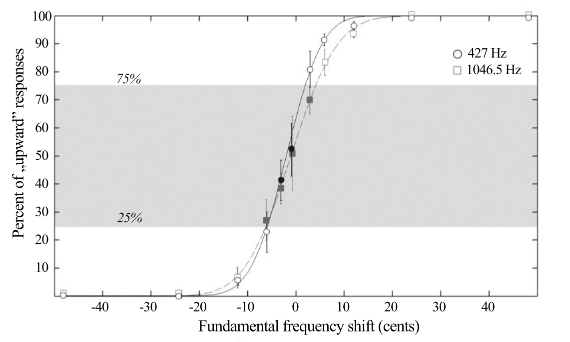

Figure 1. Average percentage (±1 standard deviation) of upward responses as a function of the f_0 shift introduced in the playback sound, at 427 and 1046.5 Hz. Filled symbols in the grey area represent values below the perception threshold.

4. Results

Just noticeable differences in fundamental frequency for the two different frequencies are presented in Table I (perceptual task). Motor reactions to f_0 changes observed for all violinists are presented in Table II (motor task).

Numbers marked in grey font show the values of motor reactions for changes, which were identified as being below the perception threshold in the perception part of experiment. It means that these reactions could occur without being perceived by the violinists.

Figure 1 presents the averaged results for the perception task of the experiment, i.e. the percentage of upward responses for each f_0 shift. From the equation of the accumulative standard distribution curve, threshold values for the probability of 75% were calculated. To evaluate the goodness of fit R-square was calculated. For both psychometric curves R^2 was equal to 0.99.

Averaged perception threshold values was 3.8 cents for the 427 Hz and 5.1 cents for the 1046.5 Hz sound (Table I).

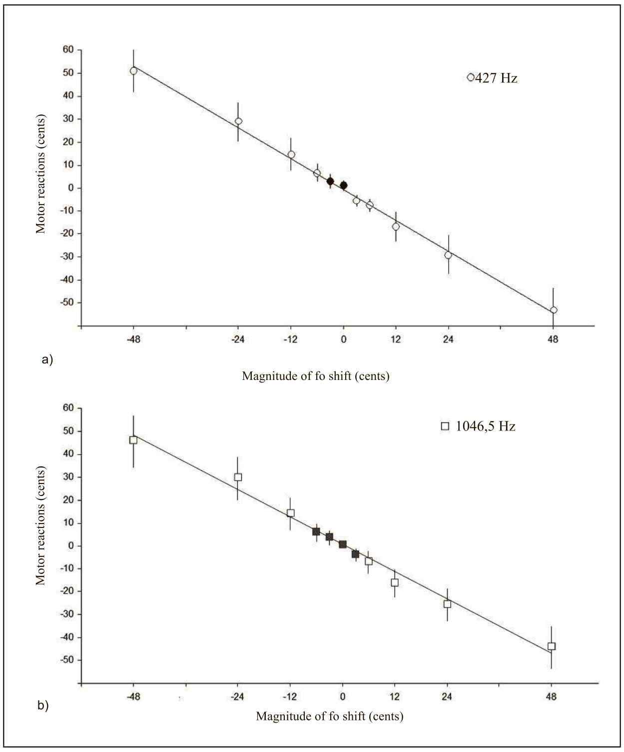

Figure 2. Averaged motor reactions (±1 standard deviation) in response to fo shifts introduced in auditory feedback for frequency 427 Hz (a) and 1046.5 Hz (b). Filled symbols represent values that are below the auditory threshold obtained in perception part of experiment.

Table II. Averaged motor responses for 427 Hz and 1046.5 Hz sound. The first column contains the applied f_0 shift value. The 2nd and 3rd column contain averaged motor responses for all violinists. Numbers marked in grey font indicate motor reactions to f_0 shifts unnoticed during playing.

f_0 shift (cents)	427 Hz	1046.5 Hz
−48	50.86	45.50
−24	28.92	29.40
−12	14.60	13.85
−6	6.52	5.93
−3	2.87	3.41
0	1.28	0.61
3	−5.46	−4.05
6	−7.38	−7.23
12	−16.80	−16.38
24	−33.90	−25.85
48	−52.89	−44.07

Similar to previous results [5], an asymmetry of the psychometric curve could be observed for both frequencies. It was easier to perceive upward f_0 shifts than downward f_0 shifts. For the 427 Hz sound, the perception threshold for upward f_0 shifts was 2 cents, while for downward f_0 shifts it was 5.6 cents. A similar case occurred for the 1046.5 Hz sound. The threshold value for upward f_0 shifts was 3.8 cents, and 6.4 cents for downward f_0 shifts.

The average motor response values are presented in Figure 2. When we look at the violinists' motor reactions in relation to the change introduced in auditory feedback, we can conclude that they compensated for the introduced f_0 shift perturbation. Namely, they raised the f_0 of the note they were playing in response to downward f_0 shifts. The opposite situation took place in response to upward f_0 shifts. The compensation was almost complete (Table II) and very coherent between violinists. The relationship between motor response and introduced f_0 shifts can be approximated by a linear function. For both played sounds R^2 value was equal to 0.99.

Based on the perceptual threshold values one can conclude that the f_0 shifts: −3 for 427 Hz and −6, −3, 3 for 1046.5 Hz sound are below the perceptual threshold (the grey areas in Table II and Figure 1). It is important to notice that a clear compensating motor reaction occurred for both subliminal and above threshold frequency changes.

Statistical analysis was performed independently for the two played frequencies of the reproduced sounds (426 Hz; 1046.5 Hz). The repeated measurements design (rANOVA) resulted in a significant main effect for the f_0 shift perturbation magnitude for both fundamental frequencies 427 Hz ($F(9, 54) = 361.614$, $p < 0.001$) and 1046.5 Hz ($F(9, 54) = 534.548$, $p < 0.001$). A post-hoc Tukey (HSD) tests showed a statistical significance ($p < 0.001$) of differences between reaction values to all frequency modifications. This means, that motor reactions differ for all the introduced changes, including those below the perception threshold. For instance, motor reactions for +3/ − 3 cents are statistically different. In both cases, the compensation occurs, but the direction of it differs and is statistically significant.

In addition to the examining differences in motor responses between two played frequencies (426 Hz; 1046.5 Hz) the regression analysis was performed. The model is statistically significant and described 89.9% of the dependent variance ($F(2, 2797) = 1259$, $p < 0.001$). However, a pair comparison shows that the significant changes between 427 and 1046.5 Hz sound apply only to values of −48, 24 and 48 (t-test with Holm correction).

5. Discussion

A number of studies have demonstrated that introducing changes to the voice fundamental frequency in auditory feedback causes the listeners to react by compensating for changes in vowels [15, 16, 17, 3] consonants [18, 19, 20, 1] and complex speech sounds [21, 2]. The response magnitude is more accurate in singing than when speaking [1]. Studies [3, 5, 6, 10] showed that motor reactions occur for minor changes below the perceptual threshold. In these cases the reactions were more precise than reactions to easily noticeable f_0 changes. For vocalization, these findings provided evidence supporting the theory of the existence of two systems for auditory information processing: the motor system, which uses the acoustic signals of self-generated sounds to automatically adjust the acoustic parameters of the voice, and the perception system, which consciously perceives changes in frequency and sound pressure level. The present study showed that violinists also react to modifications of f_0 introduced in auditory feedback. In case of violin playing, the compensation was almost complete and very precise, irrespective of the value of the frequency modification. At the same time, no major differences between compensation magnitude for the lower frequency sound (427 Hz) and the higher frequency sound (1046.5 Hz) were observed. Pair comparison shows that significant changes between 427 and 1046.5 Hz sound apply only to values of −48, 24 and 48 cents. The difference for the largest f_0 shift can possibly be explained by a larger physical gap on the instrument, that requires a shift of the finger, whereas all other shifts can be compensated by rolling the finger.

For vocalization, the reported JND was 10.5 cent [22] for singers with mixed skill level. For nonsingers depending on the experiment conditions the perception threshold was slightly higher from 15 cents [10] to 25 cents [7]. In case of violin playing JND was lower by up to 7 cents. This suggests that the auditory control of musical sounds is even more precise. Even so, some of the modifications introduced were lower than the obtained perceptual threshold. Fundamental frequency shift values of −3 for 427 Hz and −6, −3, 3 for 1046.5 Hz sound were all under the perception threshold. For these values we can still observe very precise compensating reactions to the introduced changes. This constitutes evidence that a separate motor auditory system, which uses acoustic signals (beyond perception) to automatically adjust the proper pitch of sound, exists also for musical sounds. In the future studies it would be interesting to see what effect would a further extension of this experiment have on the results i.e. the inclusion of a higher number of subjects as well as more complex musical sequences.

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