The Effect of Wearing Foam and Etymotic Earplugs on Classical Musicians' Pitch Perception

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Abstract:

The purpose of this study was to investigate the effect of wearing earplugs on classical musicians' pitch perception across three experimental conditions: no earplugs, foam earplugs, and Etymotic earplugs. Participants were graduate and undergraduate music majors attending a large school of music in the southeastern United States ($N = 72$). Participants adjusted the pitch of five complex stimulus tones (C#4, C#5, C#3, G#4, and F#3) using a continuous response digital interface until they believed the interval was in tune with an oboe (C#4) reference tone. Participants tended to tune flat when the stimulus tone was presented flat and to tune sharp when it was presented sharp across all three earplug conditions. Overall cent deviation in tuning responses showed that in both directional and absolute deviation analyses, listeners were most accurate when tuning without earplugs, then when using Etymotic earplugs, and least accurate with foam earplugs. Significant differences, however, were limited to specific intervals and in magnitudes not likely to be perceived. Although more research is needed, the use of Etymotic earplugs may provide valuable protection against noise-induced hearing loss with negligible effects on pitch perception. Implications for musicians and recommendations for future research are discussed.

Keywords: pitch perception | hearing loss | earplugs

Article:

Noise-induced hearing loss (NIHL) refers to any loss of hearing resulting from overexposure to sound. Researchers have found that sound overexposure, due to either duration or intensity, causes permanent damage to the small hair cells in the cochlea. NIHL is an occupational hazard associated with professions that require employees to be around continuous or very loud sound, such as construction workers and factory employees as well as musicians. Researchers have found that musicians may have increased risk for NIHL due to the amount of time spent in rehearsals and performances (Beach & Gilliver, 2015; Cutietta et al., 1989, 1994; O'Brien et al., 2013; Washnik et al., 2016).

To protect the hearing health of employees, the World Health Organization (WHO; 2015) and the National Institute for Occupational Safety and Health (NIOSH; 1998) have published health guidelines for sound pressure level (SPL) and hearing. Both the WHO and NIOSH recommend 85-dB SPL for 8 hr as the maximum dose of sound a person should receive daily. NIOSH reported that for every 3-dB increase, maximum exposure time should be cut by approximately 50%. For example, 88-dB SPL has a 4-hr maximum daily dose (Chesky, 2008). Sound levels have been measured during solitary practice of professional orchestral musicians and results showed that 53% of the musicians studied exceeded permissible daily doses of sound exposure during their practice (O'Brien et al., 2013). Washnik et al. (2016) examined the amount of sound exposure university students experienced daily and found that half of the participants in their study exceeded 100% of the maximum daily dose in large-ensemble rehearsals or through individual practice alone. In a survey of professional symphony performers, most musicians reported at least a small degree of hearing loss (Woolford et al., 1988). After controlling for age and other factors, the researchers determined that SPLs contributed at least in part to permanent hearing loss. Public school music teachers who rehearse ensembles also exhibited a greater frequency and magnitude of NIHL when compared with the general population (Beach & Gilliver, 2016; Cutietta et al., 1989, 1994). NIHL remains particularly concerning for musicians because hearing aids and cochlear implants provide assistance with speech intelligibility but have not yet been designed for music performing and listening.

Musicians have numerous options that have been reported to protect hearing. Changes to instrumental setup, rehearsal schedules, acoustic treatments, and rehearsal environment, among others, have been shown to reduce musicians' prolonged exposure to high SPLs (Amlani & Chesky, 2014). Orchestras surveyed by Woolford et al. (1988) reported making logistical changes to scheduling, seating, and facilities to reduce musicians' risk of NIHL. However, several researchers have shown that these changes are not always effective. For example, Behar et al. (2018) found sound attenuation for acoustical shields was between 5.8 and 10.7 dB for solo performers, but Luo et al. (2018) determined that in authentic orchestral settings, the same shields were not effective due to sound diffusion from both sides of the shield. Koskinen et al. (2010) found that acoustical damping treatments decreased sound reverberation time but overall did not reduce music teachers' sound exposure. When it is not feasible to alter the conditions of the music rehearsal/performance environment, or when treatments are inadequate, exposure to high SPLs may be reduced through the use of properly fitted and inserted earplugs (Woolford et al., 1988).

Despite the efficacy of earplugs in reducing the risk of NIHL, classical musicians have reported low earplug use. Walter (2017) reported that only 21% of surveyed undergraduate music education majors wore earplugs during practice or rehearsal, and 78% believed that surgery or hearing aids were a viable solution to correct for NIHL. "Loss of monitoring ability, alteration of timbre, uncomfortable fit, a feeling of pressure from the earplugs, and a deteriorated localization ability" were cited as the most salient reasons musicians do not wear earplugs (Huttunen et al., 2011, p. 177; Rice & Coles, 1966). Musicians have reported that earplugs hindered their performance, caused a lack of control, reduced sound quality, interfered with intonation, and created an occlusion effect, causing a hollow or booming sound in the ear (Laitinen & Poulsen, 2008).

Intonation has been identified as perhaps the most important variable when listeners determined the quality of a performance (Geringer & Johnson, 2007; Geringer & Madsen, 1989). A number of acoustical and environmental factors affect musicians' pitch perception, including timbre (Allen & Oxenham, 2014; Caruso & Balaban, 2014; Geringer et al., 2015; Wapnick & Freeman, 1980; Worthy, 2000), register (Hayslett, 1990), and tempo (Duke et al., 1988; Geringer & Madsen, 1984).

Researchers have found that timbre affected both the perception and performance of pitch (Byo & Schlegel, 2016; Caruso & Balaban, 2014; Geringer & Worthy, 1999; Hayslett, 1990; Wapnick & Freeman, 1980). Worthy (2000) found that "brighter" tones were perceived as sharp while "darker" tones were perceived as flat, compared with the reference tone of the same pitch. When asked to match pitch, participants performed more sharply to match "brighter" tones and flatter to match the pitch of "darker" tones, compared with a reference tone of the same pitch. Allen and Oxenham (2014) determined that musical training did not help participants overcome interference effects in pitch and timbre discrimination tasks reliably.

Tuning accuracy also is impacted by scale degree, harmonic context, melodic direction (ascending or descending), and initial presentation of an out-of-tune tone. For example, Geringer (2018) found that eight artist-level violin performers adjusted the tuning of various scale degrees depending on the harmonic context and their personal tuning preferences. Geringer (1976) and Hopkins (2014) both noted that the initial presentation of pitch level had an effect on tuning accuracy. Hopkins observed that when tuning a tone to a unison reference tone or a perfect fifth above or below a reference tone, participants had a strong tendency to tune pitches flat if the tone was presented initially as flat and a slight tendency to tune pitches sharp if the tone was presented initially as sharp.

There is some evidence to suggest that wearing earplugs, particularly foam or low-quality earplugs, may interfere with musicians' ability to perceive and perform with accurate intonation and may affect perceived timbre (Beach & O'Brien, 2017; Cook-Cunningham, 2013; O'Brien et al., 2014). For instance, musicians reported hearing a duller or muffled sound, and that difficulty to hear pitch accurately fostered anxiety about their intonation (Beach & O'Brien, 2017). O'Brien et al. (2014) ran a clinical trial comparing the efficacy of passive and active musicians' earplugs designed by Etymotic with 26 professional orchestral musicians. Active earplugs include some type of powered noise cancellation in addition to blocking the entrance of the ear canal, while passive earplugs reduce sound by blocking the entrance to the ear canal. Following the trial, musicians were surveyed and some reported difficulties with intonation (64%), hearing themselves (64%), hearing others (73%), and balancing with others (73%) while wearing the passive high-definition earplugs. Musicians found active earplugs more effective with the exception of balance, but these earplugs are expensive and must be custom fit to the individual ear. High-definition earplugs have been recommended as a viable solution for musicians because these earplugs reportedly reduce sound more consistently across frequencies than traditional earplugs designed for construction work, but more research is needed to verify their effectiveness.

If wearing earplugs inhibits musicians' ability to play in tune, or their perception of their ability to play in tune, then it can be difficult to convince musicians to wear earplugs, despite their effectiveness in mitigating NIHL. Therefore, the purpose of this study was to investigate the effect of wearing earplugs on musicians' pitch perception. More specifically, we investigated classical instrumentalists' tuning accuracy across three experimental conditions: no earplugs, foam earplugs, and Etymotic earplugs. Research questions included the following: (1) Is there a difference in classical instrumentalists' tuning accuracy when wearing foam earplugs, Etymotic earplugs, or no earplugs? (2) Is there a difference in tuning accuracy for different intervals? and (3) Does initial presentation of pitch, in either the sharp or flat direction, affect participant tuning?

Method

Participants

Participants were graduate (n = 13) and undergraduate music majors (n = 59) attending a large school of music in the southeastern United States (N = 72). Areas of study included music education (n = 47), music performance (n = 20), and other music-related degrees (n = 5). Primary performance area included woodwind (n = 22), brass (n = 24), percussion (n = 6), string (n = 11), and voice (n = 9). The sample included 30 males and 42 females. All procedures complied with institutional and federal regulations in the treatment of human subjects. Participants received a free pair of Etymotic earplugs upon completion of the study.

Conditions

Participants' pitch perception was tested across three conditions: no earplugs, foam earplugs, and Etymotic earplugs (ETY-Plugs). The foam earplugs were standard 3M E-A-Rsoft Yellow Neons Earplugs 312-1250. These earplugs advertise an overall noise reduction rating of 33 dB. However, attenuation is not uniform throughout the frequency spectrum, and octave bands above 1000 Hz are reduced with greater magnitude (ranging from 38 dB at 2 kHz to 45 dB at 3 and 4 kHz and 49 dB at 8 kHz). ETY-Plugs also attenuate sound in larger magnitudes for frequencies above 1000 Hz but to a lesser degree (23 dB at 2 kHz, and approximately 25 dB between 3 and 8 kHz). We selected ETY-Plugs for our study because these are used commonly by professional musicians, come in two standard sizes, and are affordable. The researcher involved in testing was trained by a hearing conservation specialist to assess fit to ensure participants had inserted the earplugs correctly prior to beginning the tuning task.

Preparation of Stimuli

The tuning task consisted of five intervals presented simultaneously with the reference tone: unison, octave above, octave below, perfect fifth above, and perfect fifth below. During pilot testing of stimuli, we asked three graduate music students to listen to simple electronic stimuli (sine and square waves) for the purpose of matching tuning tones to a reference tone. The simultaneous tuning of these tones resulted in the presence of audible beats that the students used to tune the harmonic intervals easily. To eliminate these beats, we decided to use an authentic oboe tone as the reference and constructed electronic tones as tuning tones. We used Adobe Audition CC 2018 (Version 11.1) to construct complex electronic tones with a fundamental and four additional integral multiple harmonics with a decreasing power spectrum (relative to the fundamental, Harmonics 2 and 3 were reduced in amplitude by 40 dB, and Harmonics 4 and 5 were reduced by 60 dB). Subsequent pilot-testing showed that tuning the complex tones to the oboe tone compelled the listeners to tune to the frequency of the reference tone without relying on obvious beats. We then created five complex tones to serve as the stimulus tones that participants manipulated in order to be in tune with the oboe (C#4) reference tone: C#4, C#5, C#3, G#4, and F#3. These pitches were selected because they form intervals of unison, ascending and descending octaves, and perfect fifths relative to the reference tone.

The reference tone was recorded in a recital hall designed for solo and small-ensemble performances using an iPhone7 with Shur MV88 external microphone (WAV file at 48 kHz in 24-bit resolution). The oboist was asked to perform an in-tune C#4, using a tuner as a visual guide. We chose C#4 as the reference tone because it is in a middle range and is not a pitch that instrumentalists normally use for tuning. Minor frequency adjustments to the oboe tone were made with Adobe Audition CC 2018 (Version 11.1) so that it remained within ±1 cent of the target frequency (277.18 Hz).

Response Apparatus

The continuous response digital interface (CRDI) allowed participants to manipulate the pitch of the stimulus tones by turning an unmarked dial. The CRDI and Amazing Slow Downer software have been used previously to record tuning responses of musicians (Geringer et al., 2010, 2014). We set the pitch modulation parameters of Amazing Slow Downer software (Version 3.6.1) so that the CRDI dial (a 255-degree arc) provided a tuning range of ±50 cents. The faceless dial provided no visual cues so that listeners were unable to ascertain visually the location of the middle of the dial. The dial was set so that the stimuli tone was 15 to 20 cents flat or sharp prior to each tuning trial. The only feedback, other than aural, concerning dial position was the dial stops at the two extreme end points (±50 cents).

Procedure

Each participant was tested in three conditions: no earplugs, foam earplugs, and Etymotic earplugs. Listeners were tested individually in a quiet room. Tones (reference and stimuli) were played monaurally through a Dell Altec Lansing Multimedia speaker system (Dell A425) with two speakers placed equidistant from the listener on either side. Reference and stimuli tones were set at the same loudness levels, and participants were able to adjust the loudness if desired. The reference tone was played alone first from one speaker; then the stimulus tone was presented through the second speaker concurrently. Participants adjusted the pitch of each stimulus tone until they believed the interval was in tune with the reference tone. The stimulus tones were presented initially as either sharp or flat compared with the reference tone. The degree of initial sharpness or flatness ranged from 15 to 20 cents to reduce potential bias caused by turning the dial by similar magnitudes for each trial. All tones looped continuously, allowing participants ample time to adjust the tuning until they perceived the stimulus note to be in tune with the reference tone.

To control for conceivable order effects, four different interval tuning orders and six different earplug condition orders were utilized. Potential bias resulting from the initial sharpness or flatness of each stimulus tone was balanced by presenting initially each tone sharp in two of the orders and flat in the other two. All tuning orders began with the unison interval because it is the most commonly tuned interval and allowed participants to become comfortable with the procedure. Participants were assigned randomly to one of 24 counterbalanced tuning order and condition order combinations.

Results

Raw data consisted of participants' tuning adjustments in cents deviation relative to equal temperament. We analyzed tuning adjustments two ways: One included the direction of deviations (sharp or flat), and the other used absolute values of the deviation. Means and standard deviations for both analyses of the three conditions (no earplug, foam earplug, and Etymotic earplug) and the five tuning intervals (unison, fifth above, octave above, fifth below, octave below) are shown in Table 1. Descriptive analysis of the absolute deviation responses showed that participants were most accurate when tuning without earplugs (M = 7.04, SD = 7.40), followed by the Etymotic earplugs (M = 7.94, SD = 8.00). Foam earplugs resulted in the least accurate tuning responses (M = 9.45, SD = 9.09).

Table 1. Mean Cent Deviation for Conditions by Intervals

	Directional		Absolute	
Condition, Interval	M	SD	M	SD
0, Unison	-0.25	8.68	6.31	5.93
0, P8↑	-0.65	6.37	4.79	4.22
0, P5↑	0.76	12.74	8.88	9.11
0, P8↓	-4.13	12.19	9.36	8.78
0, P5↓	-3.25	8.49	5.89	6.91
F, Unison	-1.43	10.08	6.99	7.36
F, P8↑	-3.11	9.93	7.50	7.17
F, P5↑	0.94	14.61	11.31	9.21
F, P8↓	-8.71	14.70	13.38	10.57
F, P5↓	-4.89	12.28	8.08	9.23
Et, Unison	-0.97	8.88	6.28	6.32
Et, P8↑	-2.11	8.16	6.03	5.85
Et, P5↑	-1.83	14.17	10.39	9.73
Et, P8↓	-5.11	11.25	9.58	7.74
Et, P5↓	-2.74	11.31	7.40	8.94

Note: 0 = no-earplug condition; F = foam earplugs; Et = Etymotic earplugs

The 15 tuning responses (three listening conditions by five intervals) of each participant were recorded, including the direction of their pitch response. Initially we planned to analyze the data using a repeated-measures analysis of variance (ANOVA) with one between-subjects factor (the four tuning direction orders) and two within-subjects factors (earplug conditions and intervals). However, when we screened the data to verify that the assumptions of the ANOVA were met, we found that sphericity was violated for the variable of intervals and the interaction of intervals and condition. We therefore conducted a two-way multivariate analysis of variance (MANOVA) (tuning direction order by earplug condition with the intervals as the variates) since it does not require the assumption of sphericity and we were interested in the combined effect of earplugs as a whole across the intervals. We then conducted a new power analysis. For a within subjects–factors MANOVA, results indicated a minimum sample size of 60 (we input a projected small effect size of partial η2 = .05, alpha = .05, and power level of .80).

We first analyzed tuning adjustments using the directional cent deviations. Significant multivariate main effects were found between the three conditions, F(10, 264) = 2.69, p < .004, partial η2 = .09. Univariate results showed significant differences between earplug conditions for two of the five intervals: the octave above (p = .045) and octave below (p = .006). Overall, participants were most accurate tuning without earplugs (M = −1.5, SD = 10.11), followed by Etymotic earplugs (M = −2.55, SD = 10.99). Foam earplugs resulted in the least accurate and most flat tuning responses (M = −3.44, SD = 12.66). There was a difference between the initial presentation direction of the stimulus tone, that is, when presented sharp or flat, F(15, 177) = 7.94, p < .001, partial η2 = .38. Univariate analyses showed that initial presentation of the tuning stimuli influenced responses in all four order conditions (p < .001). Table 2 demonstrates the consistency of this effect. Mean tuning deviations were in the same direction as the initial stimulus presentation for 18 of the 20 means shown. When initial stimuli were presented in the flat direction, mean deviation responses also were flat. Stimuli presented in the sharp direction also produced sharp responses with two exceptions (the octave-down and fifth-down intervals), both of which were tuned less than 1 cent flat.

Table 2. Mean Cent Deviation for Intervals by Initial Stimulus Direction.

Tuning Order	Interval				
	Unison	Octave Up	Fifth Up	Octave Down	Fifth Down
Order 1	Flat: -5.11	Sharp: +3.06	Flat: -9.09	Sharp: -0.43	Flat: -10.67
Order 2	Flat: -3.82	Flat: -6.00	Sharp: +7.82	Flat: -12.39	Sharp: +2.02
Order 3	Sharp: +4.72	Flat: -5.82	Sharp: +8.54	Flat: -12.89	Sharp: -0.24
Order 4	Sharp: +0.67	Sharp: +0.93	Flat: -7.43	Sharp: +1.76	Flat: -5.61

Note: Initial stimuli were presented either sharp or flat (±15 to 20 cents) relative to the stimulus pitch.
Shown are the initial pitch category and the mean tuning responses of listeners.

We then conducted a second analysis of the data using absolute pitch deviation from equal temperament. In the directional analysis, combining the positive and negative values resulted in means somewhat close to zero despite the large variance in participants' responses. Therefore, we converted directional data to absolute values and again conducted a two-way

MANOVA (tuning direction by earplug condition with the intervals as the variates).

Significant multivariate main effects were found between the three conditions, F(10, 264) = 2.84, $p = .002$, partial $\eta2 = .10$, and for initial tuning direction, F(15, 177) = 2.03, $p = .016$, partial $\eta2 = .14$. Their interaction was not significant ($p > .70$). Comparing earplug conditions, univariate results showed differences for tuning the interval an octave above ($p = .003$) and an octave below ($p = .002$). Subsequent Bonferroni comparisons showed that participants' tuning was more accurate wearing no earplugs compared with foam earplugs for both intervals ($p < .03$). Etymotic earplugs and no earplugs were not statistically different for the two intervals, and responses with Etymotic plugs were more accurate than those with foam for the descending octave ($p = .024$). For initial tuning direction, univariate analyses showed that these differences were significant for the two descending intervals, the octave ($p = .035$) and fifth ($p = .011$). The two descending intervals were tuned less accurately (approximately 5 cents) when stimulus tones were presented flat compared with sharp presentations. The other intervals were tuned similarly whether tuning from above or below.

Discussion

We investigated pitch perception of musicians when wearing Etymotic earplugs, foam earplugs, and no earplugs. Overall cent deviation in tuning responses showed that in both directional and absolute deviation analyses, listeners were most accurate when tuning without earplugs, then when using Etymotic earplugs, and least accurate with foam earplugs. These differences were significant only for specific intervals. Directional differences were relatively small: College student musicians tuned approximately 1 cent flatter with foam earplugs than with the Etymotic earplugs, which were tuned about 1 cent flatter than when using no earplugs. Analysis of absolute deviations found similar degrees of difference between the conditions. Although these findings may appear to provide some justification for musicians' self-reported perceptions that wearing foam earplugs interferes with how they tune and hear pitch (Cook-Cunningham, 2013; Huttunen et al., 2011; O'Brien et al., 2014), the magnitudes of the differences we found between the two types of earplugs are within the threshold of just-noticeable differences. Tuning differences between intervals ranged from 1 to 4 cents when comparing foam earplugs with no earplugs. The optimal pitch discrimination threshold of musicians is 4 to 6 cents for middle octaves (Spiegel & Watson, 1984). The practical significance of these small differences is questionable. Although it is possible that musicians could hear a difference this small given ideal listening conditions, pitch discrimination is affected by a number of variables, including intensity, direction of tone to be tuned, and tone quality in particular, among others (Morrison & Fyk, 2002).

Additionally, the initial presentation (flat or sharp) of the stimulus tones affected tuning accuracy. Participants tended to tune flat when the stimulus tone was presented flat and to tune sharp when it was presented sharp, with few exceptions. The primacy effect of the initial stimulus presentation corroborates previous findings (Geringer, 1976; Hopkins, 2014; Swaffield, 1974). Playing and singing in tune with oneself or with others in an ensemble is a recurrent and ongoing task within music performance. The initial presentation (sharpness/flatness) of an out-of-tune note seemed to influence musicians' ability to make fine-tuning adjustments. Performers and teachers should be made aware of this propensity.

We observed that in both earplug conditions, participants tuned more flat than without earplugs. Wearing earplugs may modify timbre as perceived by musicians (Huttunen et al., 2011). Researchers have noted that changes in timbre have an effect on tuning accuracy, so this explanation seems plausible (e.g., Allen & Oxenham, 2014; Caruso & Balaban, 2014; Geringer et al., 2015; Geringer & Worthy, 1999; Worthy, 2000). Although marketing information for the earplugs claims overall noise reduction magnitudes (33 dB for foam plugs and 20 dB for the ETY-Plugs), response curve specifications for the earplugs reveal increases in attenuation for frequencies 1 kHz and above (of 5 dB for ETY-Plugs and up to 16 dB for foam plugs). The harmonics used in our complex stimulus tones fall within the range of frequencies that researchers in psychoacoustics have established as decisive in pitch perception (Moore et al., 1985; Plomp, 1967; Ritsma, 1967). It seems conceivable that the decreased sensitivity to frequencies in this range may at least in part be responsible for the observed reduction in pitch acuity and increased flat responses with earplugs.

In the present study, we investigated only two types of earplugs. While we chose these types based on availability and affordability, conclusions about other types of earplugs should not be made. Investigation into more types of earplugs, such as musician custom-molded earplugs, should be conducted. Participants in our study tuned only five intervals. It is possible that musicians may learn to hear more accurately over time while wearing earplugs. Additionally, the tuning tasks in our study were designed to measure perception, not intonation accuracy within an ongoing musical performance context. Furthermore, our tuning stimuli were limited in register, spanning only two octaves (C#3 to C#5). Finally, while pitch and intonation have been identified in previous studies as prime components in the evaluation of music performance (Geringer & Johnson, 2007), they are not the only salient aspects of quality performance. As such, exploring the effect of wearing earplugs on perception and performance of other musical elements, including articulation, balance, phrasing, and tone, would increase our understanding of how wearing earplugs possibly may affect music performers, teachers, and audience members.

For both music teachers and performers, NIHL remains a serious health consideration, with earplug use being one of the most commonly recommended ways to protect hearing. The results of this study appear to comport somewhat with musicians' concerns about earplug use interfering with pitch perception, more acutely for foam earplugs than for Etymotic earplugs. As such, to preserve the integrity of pitch perception, performers and teachers might avoid the use of foam earplugs as a method of hearing protection. Instead, they should opt for musicians' earplugs, with the understanding that they may alter their perception of pitch slightly, and incorporate other methods of sound control to protect and preserve hearing.

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