

Pitch Discrimination Task Performance with Musicians Wearing Musicians Earplugs™

Published November 26th, 2015

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Background: Musicians Earplugs™ are designed to provide a flat-frequency response while attenuating sounds. These earplugs, by name, are marketed towards musicians who historically have had low acceptance rates of hearing protection devices. Musicians have been the centre of previous research efforts with Musicians' Earplugs with most research focusing on attenuation levels, usage rates, acceptance, and musicians' attitudes towards the devices. A review of the literature revealed no studies that quantified musicians' perceptual abilities with Musicians' Earplugs™. This study was approved by the Institution Review Board at the University of Cincinnati.

Purpose: The purpose of this project was to investigate psychoacoustic capabilities in normal hearing musicians with and without custom Musicians Earplugs™. Since perception is imperative to musicians, there is a need for research on how Musicians Earplugs™ impact one's perception. Due to the limited hearing protection device (HPD) usage among musicians, quantification of the perceptual effects of these devices may prove important in influencing musicians' attitudes towards HPDs.

Research Design: The research design was a within subject performance comparison across three conditions using psychoacoustic-based measures.

Study Sample: 10 college musicians with normal hearing between the ages of 19 and 30 years (mean age 24.6; median age 24.2) comprised the experimental group. A control group of 10 normal hearing non-musicians between the age of 20 and 37 years (mean age 24.8; median age 23.8) was used to assess test material validity.

Data Collection and Analysis: Hearing levels were assessed using pure-tone audiometry. Subjects were asked about hearing and balance history and musical experience. Musician subjects meeting the inclusion criteria underwent a series of pitch discrimination task procedures under 3 conditions – at 75 dBA unoccluded, at 90 dB dBA unoccluded, and at 90 dBA with the Musicians' Earplugs™. The non-musicians were only tested at 75 dB dBA to examine the validity of the test material. The test stimuli were harmonic tone complexes with a fundamental frequency simulating piano tones of C4 ($F_0=261.63$ Hz), E4 ($F_0=329.63$ Hz), and G4 ($F_0=392$ Hz). Difference limens for frequencies (DLF) were established using a method of limits paradigm and crossover values. The test used randomized stimuli presentation and a three-interval, three-alternative forced-choice (3I/3AFC) paradigm. Two-tailed t -tests were used to probe the difference between musicians and non-musicians. The effects of condition and note on crossover scores were analyzed by fitting and

comparing multilevel linear regression models.

Results: For all trials at 75 dB dBA unoccluded, there was a statistically significant difference in performance between musicians and non-musicians indicating that the test material was able to differentiate musicians from non-musicians. For the musician trials across the unoccluded and occluded (with the earplugs) conditions, several findings were observed. The effect of condition was statistically significant. Performance was better in the 90 dBA occluded condition than in the 90 dBA and 75 dBA unoccluded conditions, and performance was not statistically significantly different in the two un-occluded conditions. Models testing the effect of condition for each note separately indicated that performance was statistically significantly better in the occluded condition for the C4 and E4 trials but not for the G4 trials. Overall, performance with the Musicians Earplugs™ was better than all other conditions.

Conclusions: The results of this study indicate that musicians wearing Musicians Earplugs™ experienced some significant change in pitch perception abilities on the psychoacoustic-based measure. The change was an increase in pitch perception abilities on the psychoacoustic-based measure with the Musicians Earplugs™. There was no decrease in ability with the Musicians Earplugs™. From this study, a flat frequency response hearing protection device has proven to maintain pitch discrimination abilities.

Disclosure: Musicians Earplugs™ were purchased using funds awarded to the senior author from the National Hearing Conservation Association's Student Research Award. The National Hearing Conservation Association has no involvement in the study. The award is given to students to support research efforts.

Introduction

Background

Noise-induced hearing loss (NIHL) is the loss of auditory function due to exposure to damaging sounds.¹ Risk of NIHL increases when sound pressure levels are very high. There is interplay between exposure level and both the length of exposure and individual susceptibility. One population that is at risk for NIHL is musicians. Sound pressure levels that have been known to increase hearing damage risk in the workplace have also been recorded in bars, clubs, concert halls, and theaters; these are locations where musicians typically perform.²⁻⁷ The potential for NIHL creates a need for hearing conservation initiatives geared towards musicians.

A hearing conservation program (such as those recommended by The National Institute for Occupational Safety and Health) has one major goal: lessen a worker's risks of NIHL. The first step is to establish the level of risk by means of dosimetry and sound level measurements. Once risk has been established, conservationists aim to remove or lessen the risk through engineering controls or by limiting exposure through administrative controls. If all efforts to lessen risk fail, the last effort recommended or mandated is personal hearing protection device (HPD) usage such as earplugs or earmuffs.⁸ Despite being a last effort for most workplace conservation programs, HPD's are a readily available and viable means of preventing NIHL for anyone at risk of NIHL – including musicians.⁹ HPDs may even be the only practical option for musicians.

HPD usage is historically low among those known or presumed to be at risk of NIHL, and musicians are no exception.^{1,5-7,9,10-12} Even when musicians are aware of the NIHL and hearing conservation, they seldom use HPDs. It is interesting to note, though, that a greater number of musicians who already experience some hearing health issues are more likely to use HPDs than

those with no known or perceived issues.⁹⁻¹³ It appears that HPD usage is more so a reactive measure than a proactive conservation effort.

Several reasons cited for low HPD usage among musicians are directly related to perception. Common complaints for low usage are abnormal sound quality, inability to hear one's self, inability to hear others, increased occlusion, and autophony.^{1,6,8,9,10,12,14-16} Other non-perceptual complaints include discomfort, pain, an inability to adapt, and simply "not liking" the HPDs.^{1,6,8,9,10,12,14-16}

For those musicians who do choose to protect their hearing, there are several HPD options. Most conventional HPDs have less regard for fidelity and offer more in terms of overall attenuation level. An alternative to these HPDs is high-fidelity earplugs. Some of these HPDs have a filter that provides a balanced, flat-frequency response. In 1988, Etymotic Research designed a custom (and later universally fit) high-fidelity earplug called Musicians Earplugs™. Etymotic's team hypothesized that conventional earplugs might not be sufficient for musicians due to unbalanced attenuation (typically too much high-frequency attenuation) as well as over-attenuation.^{17,18} The argument of over-attenuation is addressed with Musicians Earplugs™ through selection of appropriate filters providing differing degrees of attenuation. The argument that balanced attenuation would be of importance to a musician is justified because pitch – which is the perceptual analog of frequency – is important to musicians and thus, ideal for examination when studying musicians and perception.¹⁹⁻²¹

The name "Musicians" Earplugs™ suggests that these devices are designed and appropriate for musicians. Manufacturers and resellers may claim that these HPDs offer unmatched clarity and quality, but these claims have less to do with any psychological or cognitive evidence and are based more on the inference that a flat-frequency response will not alter perception. Although pitch and frequency are analogous, the two are not synonymous.²² One cannot take for granted that flat-frequency response will have no effect on pitch, loudness, and timbre perception (which in turn could affect clarity and quality) without first offering research that proves that there is no effect. Additionally, frequency response is related to intensity level and thus, perception is related to loudness.²² Since Musicians Earplugs™ attenuate, there could be some additional perceptual effect due to the changes in intensity.

Musicians Earplugs™ have been examined in the past in terms of acceptance and usage rates.^{6,15} However, until more is known about the actual perceptual effects of these devices, acceptance measures that include perception cannot be accurately quantified and high usage rates cannot be expected. It is, therefore, the perceptual effects of Musicians Earplugs™ that are of interest and the focus of this study. Since perception is imperative to musicians, there is a need for research on how Musicians Earplugs™ impact one's perception.

The initial challenge presented in designing this study was determining a protocol that was relative to the experience of being a musician in order to provide test validity. The literature review revealed several studies that examined the physical, perceptual, and cognitive differences between musicians and non-musicians on various tasks using behavioral, cognitive, and electrophysiological methods.²¹⁻²⁸ Of these, the studies that examined perception are especially relevant to this effort and were incorporated into the research methods of this study.

By name and design, the balanced, flat-frequency response of Musicians Earplugs™ infers that this type of filtration is important to musicians. Frequency response is related to pitch perception and

pitch perception is in turn of importance to musicians. Therefore, it is pitch perception that was examined in this study. Since pitch perception is a subjective experience, a psychoacoustic measure must be employed. One such psychoacoustic measure that examines pitch perception is a difference limen for frequency test (DLF). The DLF test measures the just noticeable difference between two frequencies.²² Many researchers have found that musicians have smaller DLFs than non-musicians.^{19,21,23,29} Musicians may inherently have, or developed through experience and training, a heightened sense of perception as opposed to non-musicians. A DLF test is therefore sensitive to a musician's perception abilities and an appropriate paradigm as the variance in DLF scores can differentiate between musicians and non-musicians

DLFs are most commonly tested using pure-tone stimuli.²² Testing a musician's ability with pure tones greatly diminishes any real world value and questions external validity. Music is dynamic, complex and broadband; it is rarely (and more likely never) consisting of pure tones. Therefore, testing pure tones would not be as unique to the musician's perceptual experience.^{21,30} Pitch perception of pure tones is dependent more on frequency, so testing a filter with flat-frequency response should yield no change in perception theoretically. However, perception of complex sounds such as music is more dependent on the fundamental frequency as well as partials (and to some extent phase and duration).^{22,31} Additionally, it is the relationship between pitches that becomes important when one perceives aspects such as timbre and melody.^{20,32} Testing only pure tones in isolation does not fully simulate the physical properties of music. It is important then to assess perception using relevant stimuli such as complex sounds.

Recently Nikjeh et al. examined the pitch discrimination and vocal production of musicians and non-musicians.²¹ While the main focus of this project was on vocalists, the paradigm created for both tasks were found to be highly sensitive in terms of differentiating musicians from non-musicians on perception and production. It is the pitch discrimination paradigm that is relevant and applicable to this study. The frequency discrimination task developed by Nikjeh et al. used "three randomly ordered harmonic complexes" that "simulate piano tones" and "represented the mid-frequency of the untrained female voice".²¹ Using these parameters, Nikjeh et al. found that musicians had a smaller average relative DLF percentage than non-musicians.

While many portions of the Nikjeh et al. study have been adopted, the design of the current study's protocol was altered so therefore, this study is not an exact replication.²¹ Most notably, Nikjeh et al. used an adaptive stair-casing psychometric function to establish DLFs.²¹ The purpose of this study is to compare performance under various conditions (i.e., with and without earplugs) – not establishing thresholds. The adaptive nature of the stair-casing method would not allow for a repeatable method for each condition. Therefore an alternative psychometric function is preferred. For this study, a method of limits function has been utilized. The method of limits function is not ideal for establishing DLFs as it may result in overshoot of thresholds.³³ However, the method of limits function will adequately answer the research questions set forth in this study. Additionally, the non-adaptive nature of the method of limits allowed for creation of stimuli in a CD format. The ability to present the method of limits via CD allowed for a controlled, repeatable test that could be used to measure changes in performance using a scoring method described below as well as mean crossover and relative DLF comparisons.

Methods

Location

This investigation took place at the University of Cincinnati's School of Allied Health Sciences. All procedures were conducted in the school's Audiology Clinic.

Participants

Data were collected from a total of 20 participants between the age of 19 and 37 (mean age 24.7; median age 23.9). There were 6 males and 14 females. Ten normal hearing college musicians between the age of 19 and 30 years (mean age 24.6; median age 24.2) comprised the experimental group (see Table 1). A control group of 10 normal hearing non-musicians between the age of 20 and 37 years (mean age 24.8; median age 23.8) was used to assess test material validity. The musician group comprised of 6 males and 4 females. Subjects were recruited by word-of-mouth and through university-approved flyer postings at the University of Cincinnati campus. Subjects were included in the study if otoscopic examination was unremarkable, tympanometry results were within normal limits, and pure-tone audiometry revealed normal hearing (no thresholds over 20 dB HL at 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz).

None of the subjects were compensated for participating in the hearing evaluation and pitch discrimination tasks. The musicians were allowed to keep the Musicians Earplugs™.

Participant Classification

The term "musician" is a broad, encompassing term that is sometimes undefined and over-extended in research studies that involve musicians. For the purpose of this study, a musician was defined as: (1) an instrumentalist and/or vocalist; (2) a student currently enrolled at the University of Cincinnati's College of Conservatory of Music; and (3) having received at least five years of formal training.

All respondents met the inclusion criteria. No subjects were removed.

Table 1. Musician Subjects – Instrument and Experience

Subject	Primary Instrument	# Years w/ Primary	# Years Formal Training
2	Violin	20	15
3	Oboe	14	14
5	Piano	24	20
6	Double Bass	10	10
8	Percussion	10	8
9	Piano	14	14
13	Piano	19	19
15	Guitar	13	6
16	Piano	20	20
19	Percussion	8	5

	Mean	15.2	13.1
	Median	14	14

Materials

The hearing evaluation and pitch discrimination tasks were carried out in an acoustically-treated sound booth suitable for testing hearing thresholds. Tympanometry was conducted outside of the sound booth in the same room. A GSI-61 (Grason Stadler) audiometer was used for pure-tone threshold testing. TDH-39 headphones were used as a transducer. A GSI TympStar (Grason Stadler) was used for tympanometry. For the pitch discrimination task, the test stimuli were routed from a CD to loud speakers via the GSI-61 audiometer. The subject sat in the center of the booth facing two loudspeakers positioned at 45 degrees.

The audiometer routes signals in dB HL (Hearing Level), so dBA levels were converted to HL using a Brüel & Kjær 2250 sound level meter prior to testing. A calibration tone was used with a 1/2 Free Field Microphone. Calibration was completed prior to data collection, twice during collection, and at the end of data collection. In all instances, 75 dBA was calibrated at a dial-setting of 66 dB HL on the audiometer and 90 dBA at 80 dB HL.

Test Material Creation

The test stimuli were modeled after the protocol from a previous study reported by Nikjeh et al.²¹ The stimuli were created using Audacity®, a sound processing software application. The stimuli consisted of harmonic tone complexes with a fundamental frequency simulating piano tones of C4 ($F_0=261.63$ Hz), E4 ($F_0=329.63$ Hz), and G4 ($F_0=392$ Hz). Each complex contained a fundamental frequency and three harmonics. The fundamental frequency was considered to also be the 1st harmonic. The 2nd, 3rd, and 4th harmonics were divided by its harmonic number to establish the respective amplitudes. Therefore, the fundamental frequency had an amplitude of 1, the 2nd harmonic a relative amplitude of 0.5 (compared to the fundamental), the 3rd harmonic a relative amplitude of 0.33, and the 4th a relative amplitude of 0.25. The harmonic complexes were arranged in sets of three. The frequency of one of the three stimuli complexes was altered in each set. This complex was known as the target. The location of the target within each set was randomized using a random number generator. Each harmonic complex was presented for 200 ms with 300 ms between complexes within the set with a 10 ms rise and fall time. There was a 2 second interval between sets for participant response time. Ten sets constituted a run and eight runs constituted a trial. Each trial contained two psychometric functions:

1. Method of Limits Descending in which the frequency was altered in the first run by a 6% increase and descended to 0% by the end of the run.
2. Method of Limits Ascending in which the frequency was increased to +6% by the end of the run.

For the purpose of this study, each trial was limited to eight runs in order to maintain interest and motivation in the tasks. Psychometric testing can result in bored and inattentive subjects, so it is important to not fatigue the subject as performance can suffer.³³ Each trial lasted approximately 4 minutes and 15 seconds.

The percentage change in the frequency was created using the same interval as Nikjeh et al.²¹ (see Table 2). The first run contained a 6% change in frequency. The second run contained a 3% change. The remaining runs contained a change of 0.375%. The percentage change was calculated using the frequency of the previous run. This pattern resulted in frequencies that exceeded the

standard in the final set. The final target was therefore slightly less than a 0.375% change, as the standard complex was used instead.

The stimuli were exported to WAV files and burned to a CD using iTunes. Each trial comprised a track on the CD. There were 3 trials per standard F0 for a total of 9 trials. The CD also contained 30 seconds of each harmonic complex for calibration and a practice track with 2 runs.

Table 2. Percentage change in frequency for of C4 tonal complex. This example is for the method of limits descending run. The presentation is reversed for the ascending run. The same percentage change in frequencies was used for the E4 and G4 tonal complexes.

Run	C4 (261.63)	2 nd Harmonic	3 rd Harmonic	4 th Harmonic	% Change
1	277.33	554.66	831.98	1109.31	6
2	269.01	538.02	807.02	1076.03	3
3	268.00	536.00	804.00	1072.00	0.375
4	266.99	533.99	800.98	1067.98	0.375
5	265.99	531.99	797.98	1063.97	0.375
6	265.00	529.99	794.99	1059.98	0.375
7	264.00	528.00	792.01	1056.01	0.375
8	263.01	526.02	789.04	1052.05	0.375
9	262.03	524.05	786.08	1048.10	0.375
10	261.63	523.26	784.89	1046.52	0.375

Procedures

Screening and Musicians Earplug Fitting

Prior to screening all participants answered a brief questionnaire. The questions included gender, age, hearing health history, primary instrument(s) played (or vocalist), number of years playing the primary instrument (or as a vocalist), and number of years of formal training.

Next, all participants underwent an otoscopic examination, pure-tone air-conduction testing at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz, and tympanometry. The non-musicians who were confirmed as having normal hearing underwent the pitch discrimination testing immediately after the hearing screening as described below.

Once normal hearing status was confirmed for the musicians, earmold impressions were taken in order to make the custom earplugs. Each musician participant received 1 pair of custom Musician's Earplugs™ with an ER-15 filter. All earplugs were manufactured by Westone (style ER-49, silicone material). Upon receipt of the earplugs from the manufacturer, the musician participant returned to the clinic for the pitch discrimination testing. Once the musicians returned, an otoscopic examination was conducted to ensure that ear canals were clear. The senior author then verified the fit of the earplugs visually. The subject was instructed on insertion, removal, care and handling and provided warranty information. The subject was asked to report any discomfort at any point during testing.

Discrimination Task Procedure

For the discrimination task procedure the subject was seated in a designated position at the center of a sound-proofed booth. The investigator then left the booth and administered the test from

within an adjacent booth. The investigator presented the test stimuli via CD in order to establish relative difference limens for frequencies (DLF) using a three-interval, three-alternative forced-choice (3I/3AFC) paradigm. The participant was instructed to identify the target (the unique complex of the three) within each set. The participant responded verbally as to which of three complexes contained the target by stating “one,” “two,” or “three.” The responses were recorded on the scoring sheet that contained values of 1 to 10 that correspond to each set in the run. Runs were set such that the lower the number of the run the greater the difference in frequency between the target and the standard. Run 1 was always the greatest percentage change in target frequency and a run 10 was always the least. The relative DLF for each run was the crossover point. This is the point in which the all targets were correctly identified in the run and was the first incorrect response in the run.

For the musicians, there were 3 test conditions for performance comparison with each condition containing 3 unique trials. That is, each condition contained a trial where the harmonic complexes are centered around musical notation C4, E4, and G4. The CD therefore contained 9 total trials each having randomly ordered sets and trials. In the first condition, the subject was not wearing earplugs and presentation level was 75 dBA. In the next condition, the subject was not wearing earplugs and presentation level was 90 dBA. This level simulates a sound pressure level in which hearing protection would be warranted if the sound were continuous over an extended period of time. Note that 90 dBA is not hazardous if exposure time is limited. OSHA states that allowable daily exposure time is 8 hours for continuous noise levels at 90 dBA (OSHA, 1998). Total test time at 90 dBA without earplugs did not exceed 13 minutes and presentation was not continuous. In the final condition, the subject was wearing Musician Earplugs and presentation level was 90 dBA.

For the non-musicians, 1 condition was examined. The presentation level for non-musicians was 75 dBA and testing was unoccluded only. There were no additional conditions tested. All three trials – those centered around C4, E4, and G4 – were tested. Since the protocol was adopted from a previous study, the primary purpose of the non-musicians was to act as a control group to assess test-retest reliability and validity of the material.

Data Collection and Analysis

The first task was to compare the test performance by group to assess the validity of the test material. All subjects were tested at 75 dBA unoccluded with all harmonic complexes (see Table 3). The test material and test order was exactly the same for all subjects. A two-tail t-test was used to compare performance between groups on each harmonic complex and across all complexes. Mean crossover points were used for analysis.

For all trials at 75 dB dBA unoccluded, there was a statistically significant difference in performance ($p < .022$) between musicians and non-musicians, indicating that the test material was able to differentiate musicians from non-musicians.

Table 3. Musician vs. Non-Musician Comparison - 75 dBA Unoccluded

	C4 Trial	E4 Trial	G4 Trial	All Trials
75 dBA Unoccluded	M=7.413, SD 0.583	M=7.563, SD 0.690	M=7.675, SD 0.550	M=7.550, SD 0.600
90 dBA Unoccluded	M=7.200, SD 0.461	M=7.675, SD 0.619	M=7.538, SD 0.550	M=7.471; SD 0.565
90 dBA w/ Earplugs	M=7.950, 0.544	M=7.863, 0.515	M=7.850, 0.463	M=7.888; SD 0.492

The second task was to compare musicians' performance across conditions (unoccluded at 75 dBA and 90 dBA and with earplugs at 90 dBA). Multilevel (or "mixed-effects") linear regression models were fit to the musicians' data using the lme4 and lmerTest packages in R.³⁴⁻³⁶ Multilevel models allow for variability between individual subjects in designs with multiple observations for each subject. The model included indicator variables for note (C4, E4, G4) and condition (75 dBA unoccluded, 90 dBA unoccluded, 90 dBA occluded).

The effect of note was not statistically significant. Overall performance did not vary statistically significantly across the three notes. On the other hand, the effect of condition was statistically significant. Performance in the 90 dBA occluded condition was statistically significantly better than performance in the 75 dBA unoccluded condition ($p = .033$) and the 90 dBA unoccluded condition ($p = .002$). The two unoccluded conditions were not statistically significantly different from one another ($p = .529$).

Table 4 provides descriptive statistics for each combination of note and condition. In order to more fully understand the pattern of results given in Table 4, regression models were also fit to subsets of the data to test the effect of condition for each note. Both the descriptive statistics and the fitted model parameter estimates indicate that performance was as good as or better in the 90 dBA occluded condition than in either unoccluded condition, but not every difference was statistically significant.

For the C4 trials, the 90 dBA occluded condition was statistically significantly better than the 90 dBA unoccluded condition ($\beta = 0.75$, $SE = 0.15$, $p = 0.001$) but not statistically significantly better than the 75 dBA unoccluded condition ($\beta = 0.54$, $SE = 0.25$, $p = 0.057$). For the E4 trials, the 90 dBA occluded condition was statistically significantly better than the 75 dBA unoccluded condition ($\beta = 0.30$, $SE = 0.13$, $p = 0.047$) but not statistically significantly better than the 90 dBA unoccluded condition ($\beta = 0.19$, $SE = 0.11$, $p = 0.114$). For the G4 trials, the 90 dBA occluded condition was statistically significantly better than the 90 dBA unoccluded condition ($\beta = 0.31$, $SE = 0.13$, $p = 0.041$) but not the 75 dBA unoccluded condition ($\beta = 0.18$, $SE = 0.15$, $p = 0.271$). The two unoccluded conditions were not statistically significantly different for any note (C4: $\beta = 0.21$, $SE = 0.19$, $p = 0.295$; E4: $\beta = 0.11$, $SE = 0.11$, $p = 0.315$; G4: $\beta = 0.14$, $SE = 0.15$, $p = 0.385$).

Table 4. Musician Performance across Conditions

	C4 Trial	E4 Trial	G4 Trial	All Trials
75 dBA Unoccluded	M=7.413, SD 0.583	M=7.563, SD 0.690	M=7.675, SD 0.550	M=7.550, SD 0.600
90 dBA Unoccluded	M=7.200, SD 0.461	M=7.675, SD 0.619	M=7.538, SD 0.550	M=7.471; SD 0.565
90 dBA w/ Earplugs	M=7.950, 0.544	M=7.863, 0.515	M=7.850, 0.463	M=7.888; SD 0.492

Discussion

The initial challenge when designing this study was creating relevant test material. Ideally, the test

material would be unique to the experience of being a musician. If the test material provided similar results for both groups, it would not be a strong measure to assess musicians' performance with and without the earplugs. Since there was a significant difference in pitch discrimination task performance between musicians and non-musicians at 75 dBA, the material was relevant as it

separated the two groups. The findings are similar to those by Nikjeh et al.²¹ Despite the modification in the psychometric function (from a stair-casing method to the method of limits), a significant change in pitch discrimination ability was observed between groups.

The results of this study indicate that musicians wearing Musicians Earplugs™ experienced some changes in pitch perception abilities on the psychoacoustic-based measure. Musicians' performance was as good or better while wearing Musicians Earplugs™ as in either unoccluded experimental condition, though, as described above, the pattern of statistically significant differences between the occluded and unoccluded conditions varied across the three tone complexes (C4, E4, G4).

There may have been an order effect influencing our results, as the Musicians Earplugs™ test condition was the final condition probed for all subjects.³⁶ In addition, by wearing Musicians Earplugs™, there may have been an intensity effect on pitch discrimination. With Musicians Earplugs™, there was a reduction on the amplitude of the stimuli. This reduction could in turn result in less excursion of the basilar membrane and less upward spread of masking compared to the other conditions, which could heighten frequency selectivity within the cochleae. The reduction in amplitude may have also placed the stimuli in a more optimum region on the basilar membrane - where Weber ratios (DLF/frequency) are smaller – compared to the other conditions

The variation in the pattern of results across the three tone complexes is of particular interest. One of the issues with conventional earplugs is the increased attenuation of higher frequencies. This issue likely affects pitch discrimination and can lead to rejection of conventional HPD's. The E4 and G4 complexes contained the highest harmonics probed and the differences in discrimination abilities were smaller with these complexes than with the C4 complex.

Previous studies on hearing protection devices have found a relationship exists between usage and perceptual concerns and abilities. Common complaints include abnormal sound quality, inability to hear one's self, inability to hear others, increased occlusion, and autophony.^{1,6,8,9,10,12,15,16} These complaints are true even when Musicians Earplugs™ have been used. From this study, flat frequency response has proven to maintain pitch discrimination abilities. In some instances, ability may have improved. More importantly, performance did not worsen with earplugs. The assumption that flat frequency response results in un-altered pitch perception with Musician Earplugs was proven to be true on this measure. This finding should be observed with caution. Since only one domain of perception was probed (discrimination), the results are not conclusive.

Conclusion

Musicians Earplugs™ have been researched in respect to attenuation levels, usage rates, acceptance, and musicians' attitudes towards the devices. To the authors' knowledge, this is the first effort to quantify the perceptual effects of Musicians Earplugs™. This quantification is useful for hearing health professionals in terms of patient education and device recommendation. It is also useful for musicians when considering hearing protection purchase and subsequent usage.

Undoubtedly, musicians will still have concerns in respect to HPDs. The information from this study will allow clinicians to educate musicians on the perceptual abilities with these devices. It is important for clinicians and hearing conservationists to move from assuming a device works based on the physical parameters to having the data to justify this assumption.

While the test material showed an increase in discrimination ability with the Musicians Earplugs™, these superior scores might be due to an order or learning effect and not an increase in perceptual abilities with the devices. Future research should include randomized conditions to lessen this effect. Finally, the tasks in this study examined discrimination, which is only one aspect of auditory perception. Future testing on psychoacoustic abilities with hearing protection devices should include higher levels of perception as well as testing with competing signals.

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