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ORIGINAL ARTICLE

Evaluation of hearing protection device effectiveness for musicians

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ABSTRACT

Objective: To evaluate musicians' personal attenuation and perceptions of three types of hearing protection devices (HPDs): formable foam earplugs and both non-custom and custom versions of uniform attenuation earplugs (UAEs) marketed to musicians.

Design: A mixed-methods approach was used to evaluate the HPDs. Audiometric testing obtained hearing levels at baseline and with each HPD across frequencies (125–8000 Hz) to determine personal attenuation ratings and uniformity of attenuation. Participants completed surveys over six months regarding how often they used the HPDs and their perceptions about wearing them.

Study sample: Twenty-four musicians were recruited to participate.

Results: Substantial variability was observed in the attenuation achieved among participants for each HPD type, but custom UAEs provided the most consistent attenuation across frequencies. Participants' HPD preferences were influenced by multiple factors including personal instrument and specific activity. Custom UAEs were most frequently used but usage rates continually decreased over the 6-month period.

Conclusions: Fit-testing is important to determine fit and sizing. Combining information on the effectiveness of HPDs with musicians' opinions about wearing them can inform recommendations for which types may be the most effective and feasible options for reducing sound exposures.

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Introduction

Musicians are at risk of hearing loss and other adverse auditory effects (e.g. tinnitus, hyperacusis) from exposures to loud sounds, generated by playing instruments or listening to and performing music with others. Previous exposure assessments have demonstrated that musicians are exposed above recommended limits, including professionals in orchestras (Schmidt et al. 2011; O'Brien, Driscoll, and Ackermann 2013), students in university bands (Miller, Stewart, and Lehman 2007; Walter 2011), and music instructors in schools (Behar et al. 2004; Hayes 2013; Crawford et al. 2021). Studies have found that musicians may experience a higher incidence of auditory disorders, such as hearing loss and tinnitus, than the general working population (Cutietta et al. 1994; Kähäri et al. 2003; Schink et al. 2014; Isaac et al. 2017). These disorders could be especially devastating to music careers as hearing is essential to music instruction and performance. Therefore, options to control loud music exposures for instructors and performers need to be explored.

Control strategies are limited since the exposure is from music purposefully being generated, as opposed to traditional noise. Engineering controls providing too much sound reduction may affect tone quality and too little reduction will have no substantial effect on exposure. One study reviewing the effectiveness of physical control strategies in performance halls (e.g. use of risers and screens) concluded that such modifications were unlikely to substantially reduce sound exposures (Wenmaekers et al. 2017). Administrative controls limiting exposure (e.g. schedule adjustments) are also problematic as they may affect performance and livelihood. Personal protective equipment, such as hearing protection devices (HPDs), may reduce sound exposures without restricting the time spent performing and listening to music. Furthermore, since musicians frequently perform and teach in different locations, HPDs offer a way to reduce exposure in any environment. The main concern musicians have with wearing HPDs is that by reducing exposure, the very sounds they need to hear may also be blocked or distorted.

There are several options for HPDs which may offer protection. Foam earplugs can greatly reduce sound exposure with manufacturer-determined noise reduction ratings (NRRs) as high as 33 dBA. However, foam earplugs often attenuate sound differently across frequencies, which distort sounds that affect music performance, making them difficult for musicians to use. Approximately, 30 years ago, a non-custom, filtered HPD was designed to attenuate sound levels evenly across frequencies to reduce distortion of the incoming sound (Killion, De Vilbiss, and Stewart 1988). These HPDs, sometimes referred to as uniform attenuation earplugs (UAEs) (Portnuff and Price 2019) have been marketed to musicians with the goal of making sounds safer but still clear.

Although UAEs are available, studies report that many musicians, especially students and instructors, do not wear them (Laitinen and Poulsen 2008; Olson et al. 2016). Even if HPDs can attenuate sound, they are not an effective control option if someone is not willing to use them. In a study that surveyed musicians working as teachers or performers, 84% of respondents stated they never wore HPDs during personal practice, 70% never or seldom wore any during rehearsals, and 94% never wore HPDs while teaching (Laitinen and Poulsen 2008). In

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surveys regarding HPD use among student musicians, Olson et al. (2016) reported that only 4% of respondents wore HPDs during rehearsals. Surprisingly, the same study reported that while students were not wearing HPDs, 69% of participants owned some form of HPD. If resorting to personal protection is the only feasible control for reducing exposure, it is imperative to understand the likelihood of someone actually using it.

Health behaviour theories may provide a way to understand the likelihood of musicians using HPDs. The Health Belief Model (HBM) is comprised of several constructs that predict if and why people will engage in a specific behaviour to prevent or control a health condition (Skinner, Tiro, and Champion 2015) (e.g. using HPDs to prevent hearing loss). These constructs include perceived susceptibility, severity, threat, perceived benefits, barriers, self-efficacy, and cues to action. Perceived susceptibility and severity combine to estimate perceived threat: an individual must perceive the likelihood of a severe outcome occurring for it to be considered a threat. If there is a perceived threat, the individual must believe there are advantages (benefits) to engaging in the behaviour that are not outweighed by any obstacles or negative consequences (barriers). Self-efficacy addresses a person's confidence that they can perform the behaviour while cues to action are internal or external factors that may trigger the behaviour. These constructs can be directly applied to the use of HPDs and the HBM has been suggested as a potential guide for designing interventions to increase the adoption of HPDs among musicians (Olson et al. 2016).

Commonly reported benefits and barriers to wearing HPDs are issues relating to comfort and sound perception (O'Brien and Beach 2016; Olson et al. 2016; Beach and O'Brien 2017). A unique problem for vocalists and musicians using mouthpieces (e.g. brass and woodwinds) is the occlusion effect. If a deep seal is not achieved with the HPD, elevated sound pressure levels occur behind the earplug when sound is conducted through the jaw to the ear canal (Chasin 2009; Killion 2012). Musicians have reported that HPDs can both improve and worsen the occlusion effect and sound perception (Olson et al. 2016; Beach and O'Brien 2017), illustrating both how opinions regarding HPDs are highly subjective and that individual fit is a crucial factor in HPD performance. In a survey of college music majors provided with non-custom UAEs, Chesky et al. reported significant correlations between the inability to play music while wearing these earplugs with the inability to hear the music oneself and others were producing (Chesky et al. 2009). These studies offer insight into specific issues musicians experience with HPDs but provide little information regarding musicians' opinions comparing specific types of HPD in terms of these advantages and disadvantages.

The objective of this study was to evaluate the effectiveness and musicians' perceptions of three types of HPDs: formable foam earplugs and both non-custom and custom versions of UAEs marketed to musicians. Audiometric testing was performed to determine the personal attenuation rates achieved by participants and the uniformity of the sound attenuation in order to evaluate how much they reduce and distort sound. Additionally, survey responses were collected over a six-month period to determine the frequency of HPD use and the advantages and disadvantages musicians perceived when wearing each HPD. Identifying and understanding associations between musicians' perceptions of HPD performance and the frequency that musicians used the HPDs can help to make recommendations to musicians about the most effective HPDs for specific musical activities.

Methods

Hearing protection devices

Three insertable plugs were selected for this study. The 3 M E-A-Rsoft™ Yellow Neons™ Foam Earplugs were selected because they are considered a common, affordable, and recognisable form of HPD. Preliminary discussions with musicians indicated potential participants were familiar with these and may have even used a similar HPD in the past. Furthermore, the formable foam provides an opportunity for a deep seal which may help reduce the occlusion effect (Killion 2012). The Yellow Neons™, which retail for approximately $0.20 per pair, are advertised as having mean attenuations across frequencies (125–8000 Hz) ranging from 38.4 to 49.6 dB (3M 2015). Etymotic ER20XS High-Fidelity Earplugs were selected for the non-custom form of UAEs and were available in two sizes, standard and large. Retailing at approximately $15–$20 these represented a mid-range price option with manufacturer-reported mean attenuations across frequencies (125–8000Hz) ranging from 17.5 to 23.6 dB. Westone Concert earplugs (Style 49) in combination with a removable Etymotic ER-15 filter were selected for the custom form of UAEs. The ER-15 filter provides a mean attenuation across frequencies (125–8000 Hz) ranging from 12.6 to 19 dB. These plugs are custom designed to fit into an individual's ear to ensure optimal seal and fit. These were the most expensive option (approximately $200 retail) and require expertise to perform the impression required to make the plug. Hereafter, the Yellow Neons will be referred to as "foam", the Etymotic ER20XS as "non-custom UAE" and the Westone as "custom UAE".

Participants

Instructors and graduate students in a university's School of Music and instructors in neighbouring secondary schools were invited to participate in the study. To be eligible, participants had to come to the audiology clinic for audiometric testing and be willing to complete online surveys over a six-month period regarding the use of the provided HPDs. No monetary compensation was provided to participants, but they were allowed to keep the HPDs provided to them at the start of the study once they completed audiometric testing. The study design was approved by the University of Iowa's Institutional Review Board (IRB# 201805771).

Procedures

Initial visit

Following the consent process, individual participants visited the audiology clinic and completed an initial survey to collect information about demographics, current and past HPD use, and attitudes regarding hearing loss and hearing protection informed by HBM constructs (e.g. perceived severity and perceived susceptibility). The research team administered an auditory health questionnaire and presented an overview of hearing conservation topics including hearing physiology, audiological damage, and perceived symptoms caused by excessive sound exposure, and recommended sound exposure limits. Simulations of speech and music representing normal hearing and hearing loss were presented using a speaker. The music simulation also included a section simulating music heard through a hearing aid. A trained clinician performed ear impressions for the custom UAE using

an open mouth method with low viscosity silicone impression material and a bite block (Pirzanski et al. 2000) that were sent to the vendor for production. Upon arrival of the custom UAE, participants scheduled a second clinic visit for individual fitting, one-on-one training for each of the HPDs, and audiometric testing. Participants were instructed to schedule the second visit during a time when they could refrain from loud sound exposures for the prior 24 h.

HPD fitting and training

Upon arrival for the second clinic visit, participants were provided with training on the proper insertion, removal, and maintenance techniques for each of the HPDs. Laminated cards with illustrated instructions were provided to participants. Starting with the foam earplugs, participants were instructed to insert them using the Roll-Pull-Hold technique, even though holding in the foam plug is not necessarily required. This task was repeated until the trained clinician determined participants achieved a good fit based on a visual inspection and communication with the participant about their level of comfort and sound perception. Participants were instructed that the foam earplugs were disposable, were provided with 12 pairs to start, and instructed to contact the research team when they needed more. The process was repeated for the non-custom UAE, and additional training was provided on cleaning, and attaching the provided cord. This process was again repeated for the custom UAE, with additional training on how to remove and insert the filters. A trained clinician evaluated the fit of all HPDs. Large size versions of the non-custom UAEs and remakes of the custom UAEs were provided based on the clinician's determination (e.g. visual inspection indicated gaps, participants reported fit, or sound perception issues). In addition to the cases that came with the custom and non-custom UAEs, an additional steel cannister with key ring attachment, and a circular, plastic snap case with chain attachment were also provided to participants for storage. Lastly, participants were shown examples of follow-up survey questions to ensure they understood what type of information would be asked of them during the six-month follow-up period.

Audiometric testing

After the training, the clinician performed an otologic examination to evaluate the status of the ear canal and eardrum and performed tympanometry testing using a TympStar (Grason-Stadler, Eden Prairie, MN) to ensure no middle ear issues were present that potentially could affect threshold testing. Pure tone audiometric testing was performed to obtain baseline unoccluded hearing thresholds and hearing thresholds with each of the HPDs at the following frequencies: 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. A modified Hughson–Westlake technique was employed using 2-dB increments. Audiometric testing occurred in a sound-treated booth with HDA 200 circumaural audiometric headphones (Sennheiser, Old Lyme, CT) using an Otometrics Madsen Astera (Natus, Shaumburg, IL) audiometer. Baseline hearing thresholds were recorded first. Participants were then instructed to insert the first set of HPDs and completed another round of threshold testing. All thresholds were recorded in Excel (Microsoft, Redmond, WA). The order for testing the HPDs was randomised.

After testing, participants were encouraged to try the different HPDs during group rehearsals, performances, personal practice, and individual lessons over the next few months. Additionally, participants were encouraged to use the HPDs during any other activities they wished, such as recreational sports or social events. Participants were neither instructed nor required to wear the HPDs for any set amount of time.

Follow-up surveys

Follow-up surveys were administered to participants one week, one month, three months, and six months after testing to collect information regarding frequency of use and perceptions about each of the HPDs. Electronic surveys were administered *via* Qualtrics (Qualtrics, Provo, UT). Emails reminding participants of upcoming surveys were sent one week prior to the survey for all surveys except for the first week. Participants were asked to indicate how much time they spent in group rehearsals, individual lessons, personal practice, and performances during the previous week and then asked how much of that time was spent wearing each type of HPD. From these responses, the percent time spent in each activity wearing each HPD was calculated. This calculation was completed to differentiate between participants who did not wear HPDs during certain activities because they did not want to wear them and those who did not have an opportunity to do so. Participants were asked to rate the HPDs for comfort, cost, worth, sound perception, perceived protection, and ease of insertion (e.g. perceived benefits and barriers and self-efficacy). Participants rated each type of HPD using slider bars ranging from 1 (not at all) to 10 (extremely) on an ordinal scale. Zero was an option on the scale to indicate not having used any HPD. Two additional open-ended questions asked participants to provide any additional information regarding the positive and negative aspects of wearing each type of HPD.

Data analysis

Audiometric testing

To compute personal attenuation (dB), unoccluded baseline hearing threshold levels were subtracted from occluded threshold levels to determine the insertion loss achieved at each frequency for each type of HPD. Because music instructors need HPDs to attenuate similarly across the range of musical tones generated, we assessed the uniformity of attenuation by calculating a Personal Attenuation Coefficient of Variation. This was calculated for each ear tested by dividing the arithmetic mean of personal attenuation levels across frequencies by the standard deviation and multiplying by 100. This CV was used as a measure of potential sound distortion for each type of HPD, where a smaller CV indicates less distortion than a higher CV. For example 15 dB of attenuation across all frequencies would result in a mean across frequencies of 15 dB, a standard deviation of 0 dB, and a CV of 0%, indicating a completely flat response.

Surveys

Initial surveys were assessed to summarise participant demographics and determine the frequency and percent of HPD use by type. Relevant to the HBM, participants' perceptions regarding the severity of and their susceptibility to hearing loss and tinnitus were summarised. Open-ended questions regarding current perceptions of wearing HPDs and the reasons participants volunteered to participate in the study were reviewed and summarised.

Follow-up survey responses were summarised, and Kruskal–Wallis tests were used to determine if there were significant ($p < 0.05$) differences in HPD ratings over time. Changes in use frequency (how often participants wore each type of HPD)

Table 1. Study participant demographics collected in initial survey.

Factors	Description	Count	Percent
Age group	20–29 years	12	50.0
	30–39 years	3	12.5
	40–49 years	2	8.3
	50–59 years	4	16.7
	60 and over	3	12.5
Use of HPDs	Ever used	17	70.8
	Currently use	7	29.2
Currently experiencing hearing loss[a]	Yes	4	16.7
	No	12	50
	Unsure	8	33.3
Currently experiencing tinnitus[a]	Yes	6	25
	No	13	54.2
	Unsure	5	20.8

[a]Self-reported.

were examined over time using mean and standard deviations of self-reported use. To examine whether lower reported use frequencies occurred with individuals giving less favourable survey responses (e.g. "uncomfortable" and "difficult to insert"), Spearman correlations were computed. Responses to open-ended questions in the follow-up surveys were reviewed by the research team and a separate researcher, with a background in both audiology and music, to identify any additional information provided by participants that could be used to understand HPD use and to improve future surveys. These responses were grouped into common themes for reporting.

Results

Initial survey

Twenty-four musicians were enrolled in this study between August 2018 and January 2019 (Table 1). One participant did not complete audiometric testing, and a second had profound hearing loss in one ear, resulting in a total of 45 ears assessed. Most participants reported performing (79%) and instructing (75%) activities in their jobs. Participants were engaged in multiple music areas, with the largest proportions playing brass (25%) and string (25%) instruments. Half of the participants indicated they were either currently experiencing hearing loss (16.7%) or were unsure (33.3%). One quarter of participants reported currently experiencing tinnitus (25%), and an additional 20% were unsure.

All participants perceived a susceptibility for hearing loss (median= 7.0, IQR= 6.0 – 9.0) and considered the consequences of developing hearing loss to be severe (median = 10.0, IQR= 9.0 – 10.0). The same questions regarding tinnitus yielded similar results, although participants felt they had lower susceptibility to tinnitus (median= 6.5, IQR= 4.5 – 8.0) compared to hearing loss. All participants reported they agreed with the statement that "other musicians around me think wearing a HPD during musical activities is important" (median= 6.0, IQR= 5.0 – 8.5) more than the statement that "other musicians around me frequently wear a HPD during musical activities" (median= 3.0, IQR= 2.0 – 5.5). Scores below five indicate disagreement with the statement.

Seventeen participants (71%) reported trying some form of HPD for music activities before the start of this study. Twelve participants (50%) had tried foam, 11 participants (46%) had tried a non-custom UAE, and two participants (8.3%) had tried a custom UAE. Only seven participants reported that they currently used HPDs during musical activities; two used foam, four used a non-custom UAE, and one used a custom UAE. Seven participants also reported using some form of HPD for non-musical activities which included lawn-mowing, sporting events, and social activities.

Four main reasons were cited by those not currently using HPDs for musical activities. Of the 17 not previously using HPDs, eight reported sound distortion as the main reason. Four reported they did not feel that they were at risk for any damage and thus did not need a HPD. One reported the expense for an effective device kept them from using HPDs, and four reported they were not sure or that it was a new idea to them. The reasons participants reported for volunteering to participate in the study were wanting to: learn about hearing protection options (63%), protect their hearing (38%), help other musicians including their students (25%), receive HPDs (8%), and to have their hearing tested (4%).

Audiometric testing

Twenty-three participants completed audiometric testing ($n = 45$ ears). Table 2 contains a summary of personal attenuation data from study participants along with the manufacturer-reported attenuation data for each HPD in the study for comparison. Additional figures illustrating the individual attenuation data are provided in the supplemental material (Supplemental Figure 1(a–c)). Personal attenuation varied substantially by HPD type, and the HPDs with the greatest attenuation variability were the foam. For all three HPDs, participants achieved more attenuation at higher frequencies than at lower frequencies. When compared to manufacturer ratings, the greatest variability in the attenuation difference was for the foam. The CV across nine frequencies for each ear indicated the flattest response was achieved with the custom UAEs (Table 3). The median CV for each HPD type was similar (28 – 32%), and all three ranges indicate substantial variability in performance for the participants, but the range was much smaller for the custom UAE.

Follow-up surveys

Of the 23 participants who completed audiometric testing and received HPDs, 18 finished the Week-1 survey (78%), 20 finished the Month-1 survey (87%), and 19 completed the Month-3 and Month-6 surveys (83%). Use frequency for all three HPDs decreased over the six-month period. The custom UAE was the most frequently reported HPD used for all four activities: individual lessons, group rehearsals, personal practice, and performances. HPDs were rarely used for performances. Figures illustrating use frequency for these activities over time are provided in the supplemental materials (Supplemental Figure 2).

For both the custom and non-custom UAE, a participant's confidence in maintaining their performance technique was significantly correlated ($p < 0.05$) with their use frequency of the HPDs in individual lessons, group rehearsals, and personal practice. A complete table of correlations is available in the supplemental materials (Supplemental Table 1). While not strong correlations (0.31 – 0.44), these trends indicate that the more confident participants were, the more likely they were to use HPDs. For the custom UAE, additional significant correlations were observed between use during personal practice with both ratings for comfort (0.29) and confidence in inserting the HPDs (0.25). For the non-custom UAE, significant correlations between use frequency and comfort were observed during group

Table 2. Mean attenuations (sd) for each type of HPD across frequencies reported by manufacturers compared to study participants ($n = 45$).

	Foam		Non-custom UAE		Custom UAE	
Frequency (Hz)	Manufacturer	Participants	Manufacturer	Participants	Manufacturer	Participants
125[a]	38.4 (4.8)	27.5 (11.0)	19.2 (2.8)	9.5 (4.8)	16.1 (4.6)	15.2 (3.9)
250	40.3 (4.8)	28.6 (12.2)	17.5 (2.7)	14.0 (4.8)	16.4 (4.1)	17.3 (4.5)
500	43.2 (5.0)	29.6 (12.6)	20.4 (3.3)	17.1 (4.9)	16.3 (3.3)	17.5 (4.8)
1000	41.8 (4.0)	30.3 (11.2)	21.2 (2.7)	18.8 (3.7)	14.4 (2.3)	16.2 (2.9)
2000	38.6 (2.6)	37.6 (7.4)	25.1 (3.8)	22.2 (4.5)	12.6 (3.3)	12.8 (3.8)
3000	–	41.3 (8.6)	–	19.2 (4.5)	–	15.5 (4.8)
3150	45.0 (3.3)	–	23.8 (3.9)	–	15.2 (2.5)	–
4000	45.7 (3.3)	43.0 (10.7)	20.7 (3.7)	17.2 (6.4)	14.3 (2.0)	13.3 (5.2)
6000	–	48.3 (10.2)	–	18.9 (8.7)	–	17.8 (4.7)
6300	49.6 (4.0)	–	20.8 (4.1)	–	13.4 (2.6)	–
8000	47.3 (3.5)	47.2 (10.2)	23.6 (3.9)	24.3 (7.1)	19.0 (3.1)	23.2 (6.8)

Missing values indicate frequencies not measured.

[a]For 125 Hz, $n = 35$; for 3000 Hz and 6000 Hz, $n = 43$.

Table 3. Summary statistics for calculated CV (%) by HPD.

	Foam	Non-custom UAE	Custom UAE
Minimum	9	11	8
25th Percentile	18	25	23
Median	29	32	28
75th Percentile	37	41	33
Maximum	87	82	53

rehearsals (0.40) and personal practice (0.42), and between use frequency and increased sound perception ratings for group rehearsals (0.37) and personal practice (0.29). Few participants used the foam earplugs for musical activities, and thus, correlations were unable to be estimated.

Analysis of the responses to the open-ended question, "What are the additional positive aspects of wearing HPDs?", indicated several common responses. Participants identified that benefits for all three types of HPDs included 1) psychological benefit ("less worries about hearing loss" and "comfort to know that I'm protecting my hearing"), 2) reduction of post-exposure symptoms, such as headaches and tinnitus ("eliminates ringing after loud rehearsals" and "don't have a headache after practicing"), and 3) practical application in non-musical settings ("[the HPDs] assist greatly when attending loud, non-music events"). More detailed responses regarding specific types of HPDs indicated that additional benefits regarding the non-custom UAEs were the ease with which they could be inserted and removed making them the most practical for group rehearsals. One of the common benefits identified with the foam was the cost and disposability so they could be taken to events and used without worrying about losing or cleaning them.

Common barriers identified during analysis of the responses to "What are the additional negative aspects of wearing HPDs?" included 1) increased occlusion effect ("like you are playing or listening in a barrel", 2) reduced timbre and pitch perception ("sound perception of different instruments becomes altered" 3) reduced ability to hear music dynamics ("tuning and soft passages … are still difficult" and "affects my ability to hear nuances when practicing, such as … dynamic levels"), 4) insertion difficulty ("extremely difficult to fit"), 5) reduced ability to hear fellow performers/ensemble ("kind of hard … to get a sense of my sound in group rehearsal" and "difficult to hear how well the ensemble is blending together"), and 6) reduced ability to hear conversation and instruction when not performing ("harder to hear speaking from teacher" and "find myself pulling out one plug to hear my students' voices").

Discussion

This study aimed to evaluate three types of HPDs for use by musicians by first measuring the attenuation achieved by users and then collecting survey data regarding musicians' use frequency and perceptions of wearing them during various activities. Results indicate that participants achieved substantial variability in personal attenuation across frequencies for each HPD, but the largest attenuation differences, between participants and compared to manufacturer ratings, were seen with the foam (Table 2). The attenuation data for the foam may be overestimated; although the mean attenuations achieved by participants were similar to the mean attenuations reported by Berger, Kieper, and Gauger (2003), some individuals responded to testing at thresholds above what would be expected when accounting for bone conduction limits. Participants were most likely to achieve manufacturers' ratings with the custom UAE, likely because of the nature of the custom-moulded earpiece that fits best in one position. If not seated properly, the HPD will not be as effective at attenuating sound. Viallet et al. (2015) modelled attenuation with foam and moulded plugs and identified that leakages and insertion depth are the main predictors of variability in HPD attenuation, especially at frequencies below 1000 Hz, and above 1000 Hz intra- and inter-individual differences in ear canal geometry contributed to variability in achieved attenuation.

The flatness in response of the HPDs was similar to attenuation achievement because the filters perform best when seated properly, which is likely the reason that the custom UAE had smaller CV results than the non-custom UAE. Additionally, due to the rigid nature of the non-custom UAE, some participants were able to achieve better fit than others, perhaps due to anatomical differences in the ear canal which may have contributed to leakages surrounding the HPDs. The non-custom UAE came in two sizes, and the appropriate size was not always apparent to the participant or to the clinician without fit testing to assess sound attenuation. Almost one-third of our participants needed the large size of non-custom UAE, and one participant was fitted with one small and one large UAE. For musicians purchasing these HPDs on their own without fit testing, it is likely some of them will purchase the incorrect size. Without proper size and insertion of these HPDs, leakages may cause more sound to enter the ear canal, especially in lower frequencies, which may affect the uniformity of response. Foam earplugs can produce uniform, or near uniform, responses when inserted deep enough in the ear canal (Berger 2013) so it is likely the flattest responses from the foam were from participants who were able to achieve a deeper fit when inserting them. Deeply inserted foam earplugs, however, will likely result in too much attenuation for musicians.

These results reinforce the need for fit testing for both custom and non-custom forms of HPDs to ensure best fit. Consultations and audiometric testing with the clinician identified seven participants that needed a larger size of non-custom UAE and five participants that needed remakes of custom UAE due to issues with fit or sound distortion. These participants described the plugs as too large to fit comfortably or they were experiencing the occlusion effect. Fit check systems are available from some HPD manufacturers that allow for a quick assessment of individual fit of certain HPDs. The foam earplugs in our study can be used with the 3M™ E-A-Rfit™ Validation System. As of this time, there are no similar fit check systems for the musicians' earplugs. Without a fit check system available, a clinician would have to perform audiometric testing to ensure UAE have been effectively made, fit and are providing effective attenuation for users (Portnuff and Price 2019). However, audiometric testing in the clinic could be costly and is time-consuming compared to validation with a fit check system. Limited guidance is available on the best way to assess UAE performance. Although using Real-Ear Attenuation at Threshold (REAT) measurements in a sound field with masking in the non-test ear may be the most accurate method of evaluating UAEs, using REAT measurements under circumaural headphones is also acceptable (Portnuff and Price 2019). It would be beneficial for musicians to visit an audiologist with a REAT under headphone system who could determine the attenuation achieved with specific HPDs.

Hearing conservationists have long argued that "the best hearing protector is the one that the worker will wear" (NIOSH 1998). Survey responses offered insight into what contributes to the effectiveness of HPDs for musicians. The fact that most participants had tried a HPD in the past (71%), but only two (8%) consistently wore HPDs at the start of the study illustrates that this group was interested in learning about how to protect their hearing but had not been successful in finding the right kind of HPD. Future studies should investigate how to keep participants interested in hearing protection over time in order to increase long-term adoption. In this study, HPD use in general declined between the 3- and 6-month follow-up periods, so re-engagement at around 3 months may be warranted.

Many studies have found that the most predictive construct in the HBM regarding the adoption of a health behaviour is perceived barriers (Skinner, Tiro, and Champion 2015). The barriers identified by our study participants were similar to those reported in other studies. Specifically, decreased auditory perception is frequently reported as the main disadvantage to wearing HPDs during musical activities. A 2016 study found that 64% of musician participants reported decreased auditory perception as the main issue for not wearing HPDs (Olson et al. 2016). A year later in 2017, Beach and O'Brien further broke this category down into issues with sound quality, judging balance, intonation, tone and timbre, and the occlusion effect. These categories match closely with what participants in this study reported. If issues with HPD performance are, at least in part, due to fit issues that can be addressed by audiologists or other professionals early during fit testing, it is possible that some of these barriers can be reduced which may help support HPD adoption.

Examining use frequency of HPDs in combination with ratings and open-ended survey responses provides insight into how musicians may navigate the benefits and barriers of wearing HPDs during specific tasks. One participant who primarily played a brass instrument described being unable to wear HPDs during performance or rehearsals due to the occlusion effect, but the brass player found the custom UAE helpful to reduce loud sounds when teaching lessons or attending loud musical events: "The custom plugs do work well for activities not involving me playing my instrument. I am able to hear and understand someone speaking and they work well for listening to students or in a loud setting (when I'm not performing)." Another described the ease of insertion for the non-custom UAE made them ideal for group rehearsals even though the sound quality from the custom UAE was superior: "The non-custom ear plugs are extremely easy to take out and put back in. This means that while in group rehearsals and performances, I can use them easily when I need to and remove them when I don't. This being said, I have found the custom-fit ear plugs to be superior to my ability to hear others around me in a much more natural way."

Responses to the open-ended questions also illustrated the complexity of selecting a preferred HPD. For instance, some participants found the non-custom UAEs uncomfortable: "The non-custom [UAEs] were stiff and uncomfortable after about 30 minutes of use." However, others reported the opposite: "The non-custom [UAEs] were comfortable for several hours." Additionally, some participants reported decreased sound perception when wearing all types of HPDs, while others actually thought the UAEs helped them to hear their students more clearly. Having multiple options of HPDs for musicians to try may be beneficial to choose between multiple features and specific needs of a given instructional or performance task.

The small sample size was a limitation in this study. With 23 participants completing audiometric testing, there were limited data to analyse for associations with survey responses, but these tests resulted in personalised assessments of HPD performance. Additionally, requiring participants to insert HPDs themselves after an introductory training, helped to understand the attenuation that new HPD-users may expect to achieve outside of the clinic. The study was limited to the evaluation of only one type of each HPD: using different models and manufacturers may have resulted in different survey responses. The survey developed for this study has not been validated but was created based on constructs of the HBM and modelled after surveys available in the literature. The use of self-reported data may be considered a limitation; however, previous studies have found self-reported HPD use appropriate, and especially as participants were not required to wear HPDs, they had no reason to mispresent their use frequency or perceptions (McCullagh et al. 2016).

Recommendations and conclusions

Audiometric testing of three types of HPDs identified substantial variability in the personal attenuation achieved by new users trained on insertion techniques. Fit testing is critical to optimise fit, assess comfort, and ensure appropriate attenuation and flat frequency response needed for musicians using HPDs. No single "best" HPD was identified for all study participants. The most effective HPD for each participant was influenced by multiple factors including the instruments they played and the circumstances in which they played. Thus, musicians need customised assessments of HPD fit to ensure protection is adequate. Audiologists and hearing conservation programme managers need to provide HPD options to users and be prepared to discuss the advantages and disadvantages of each type for different music activities.

UAE may provide an effective option to reduce sound exposure for musicians, but fit testing must be performed to assess both comfort and effective sound reduction. Non-custom UAE options may provide effective attenuation (i.e. reduced sound

exposure and flat response) if the size and shape are appropriate for an individual's ear, however, these study results indicate that not all users are comfortable with non-custom UAE, and many users experienced sound distortion while wearing them. Custom UAEs provided little sound distortion to participants, who were generally able to achieve a good fit when inserting them, but the difficulty in inserting them was reported to be a barrier to adoption for many users, especially during activities where sound levels were variable enough to warrant removal and reinsertion at times, such as group rehearsals and performances.

After fit-testing, practitioners should discuss specific activities with HPD users to identify potential benefits and barriers of various HPDs. Understanding what features enable musicians to wear HPDs in situations where they are exposed to excessive sound may help target future interventions by strengthening recommendations about what type may work best for specific activities. Users should be encouraged to wear HPDs during non-musical activities as well to promote hearing conservation practices outside of work. Re-engagement with participants after three months of use to discuss any issues may increase long-term adoption.

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