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Managing the Live-Sound Audio Engineer's Most Essential Critical Listening Tool

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Critical listening is the live-sound audio engineer's most essential tool for informed sonic assessment. In producing a cohesive mix that fulfills an event's aims, audio engineers affect the experience and well-being of all live-sound participants. This study compares the results from a 2020 international audio engineer survey with published research. The findings demonstrate that although in theory, engineers recognize their hearing as being their most essential critical listening tool, in practice, many have not found ways to manage their hearing and optimize their assessment ability effectively. Many engineers with impeded or impaired hearing continue to mix, believing that any negative impact on participants is minimal or nonexistent. The live-sound experience and participant health and well-being are improved by promoting and acting on appropriate hearing management practices.

0 INTRODUCTION

The live-sound audio engineer performs a pivotal and rarely understood role that contributes sonically to live performance and affects each live-sound participant's experience, health, and well-being. The process of audio engineering—the manipulation of elements in the field of psychoacoustics—is both an art and a science [1] in which the human ear plays a vital part, described in one textbook as "the most complex device in all of audio engineering" [2]. To the audio engineer, sound is information to be interpreted and used to inform action before the audience notices. These actions may contribute musically or minimize undesirable noise or unflattering acoustics [3].

Engineers produce different results, as a blend of skill, musicality, practice, creativity, sensitivity, ego, tradition, social pressures, focus, hearing ability, responsibility, and more. Michael Paul Stavrou writes: "The first time I watched a really professional sound engineer, I was completely mesmerized and amazed. He made everything look so easy and sound so incredible. Why is it that thousands of engineers struggle to get a decent sound while only a few dozen pull amazing sounds . . .?" [4].

For music to be distinguished from noise, an audio engineer must produce a balanced mix for listeners to hear meaningful musical information in a distinct way where participants "experience" the music rather than just "reason" or "interpret" it [5]. Both the musician (as sound creator) and the audio engineer (as the final human element in audio production) are influenced by their auditory senses when making judgments that affect the subsequent aesthetic musical experience [1, 6]. Their actions based on these judgments can be pivotal to the progress or success of a production [7].

The attributes required of a successful audio engineer are vast. As best practice, engineers should understand audio theory and possess highly developed critical listening skills, relying more on their hearing than any strict technical parameters, especially as sound does not always behave as an engineer may expect [1, 4]. Critical listening is the ability to compare one sound with another, perceiving individual components and nuance that contribute to an overall "global" sound. Critical listening also identifies any subtle problems so the audio engineer can act accordingly to apply the necessary fix [6,7]. This study presents and evaluates audio engineers' views on hearing management practice and the value and care of what can be described as the audio engineer's most essential critical listening tool, their hearing.

1 METHODS

In 2020, with oversight from the University of Canterbury Ethics Committee, 203 audio engineers were invited to complete an online questionnaire. Ninety-six respondents completed the 134-question survey. A significant proportion of this survey was quantitative but allowed the respondents to expand on many answers. The survey explored

Table 1. The location of the 2020 survey participants.

Number of Participants	World Health Organization Region
1	Africa
19	Americas
2	Eastern Mediterranean
22	Europe
0	South East Asia
52	Western Pacific

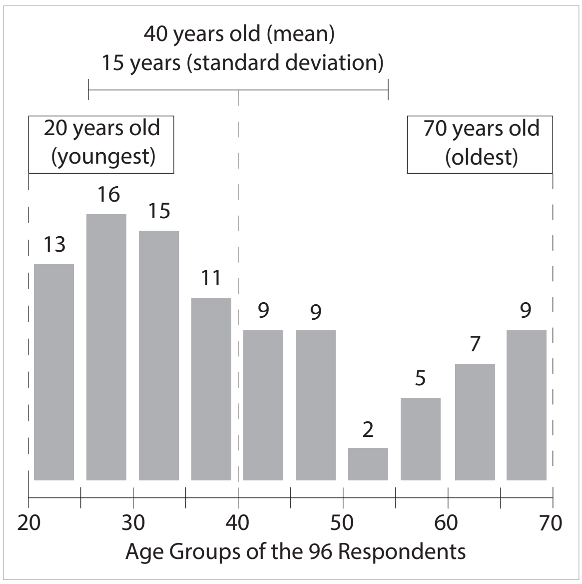

Fig. 1. The number of survey respondents within five-year age groupings.

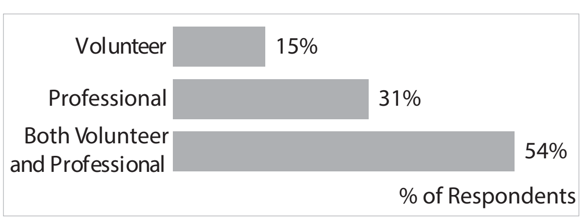

Fig. 2. The percentage of respondents who identified as volunteer and professional audio engineers.

audio engineering culture and investigated the various influences that impact audio engineer choice.

Themes and patterns drew from their responses and were coded via Qualtrics Report function, SPSS Statistics software, and manual comparison. The survey participants were audio engineers from New Zealand live-sound businesses, the Audio Engineering Society, New Zealand churches, Women in Live Music, Sound Girls, and three individuals from Facebook audio engineering groups. Respondents came from each of the six World Health Organization (WHO) groupings except South East Asia, where no engineer chose to be part of this survey (Table 1).

Fig. 1 displays the age grouping of respondents. Seventy-four participants identified as male and 22 as female. Fig. 2 categorizes the respondents' professional and volunteer audio engineering status.

Table 2. How live-sound audio engineers prepare their hearing before mixing an event.

% of Respondents	Preparation Processes
52%	Prepare in silence, resting their hearing.
44%	Prepare by referencing prerecorded tracks.
25%	Had no specific preparation routine.

Table 3. How live-sound audio engineers deal with less than ideal live-performance conditions.

% of Respondents	Methodology to Deal With Less-Than-Ideal Live-Performance Conditions
38%	"Put up" with less-than-ideal conditions; rest their ears; keep the audio level low when possible, and "do the best they can."
36%	Listen to reference tracks before a performance and walk around the venue mixing using a wireless tablet.
36%	Communicate with the band or other crew members to get and give advice and change what they can.
10%	Wear earplugs while mixing.
8%	Avoid working at that venue if they can.

2 DATA COLLECTION

The 2020 survey covered many aspects of live-sound culture. For this particular study, the data relates to audio engineer critical listening and hearing management in the live-sound environment.

2.1 Critical Listening for Live-Sound Events

Audio engineer survey respondents were asked to comment on their critical listening preparation process before mixing a live event (Table 2). They were also asked how they dealt with less-than-ideal mix position, acoustics, and stage noise (Table 3).

2.2 Personal Hearing Management

Audio engineers manage their hearing for critical listening in different ways. Some actively and consistently prepare and manage their hearing for their role, whereas others accept the risks involved and any subsequent damage as part of working in a noisy industry. While continuing to work in an industry that regularly challenges safe practice, the 2020 surveyed audio engineers identified their hearing management strategies (Table 4).

Table 4. Hearing management strategies for noisy environments.

% of Respondents	Current Hearing Management Method
77%	Regularly wear hearing protection
74%	Limit personal sound/noise exposure
64%	Monitor personal sound/noise exposure
64%	Consciously allow rest periods

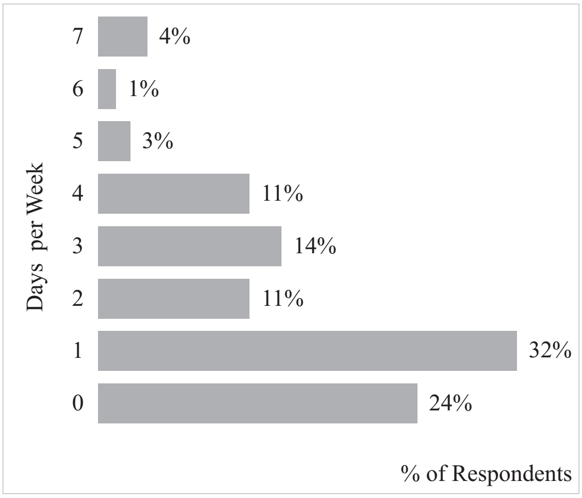

Fig. 3. The number of days per week on average audio engineers exceed World Health Organization sound exposure recommendations.

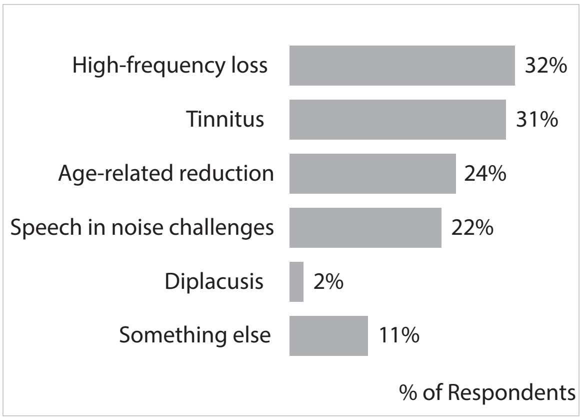

Fig. 4. The percentage of respondents who experience various hearing types of hearing challenges.

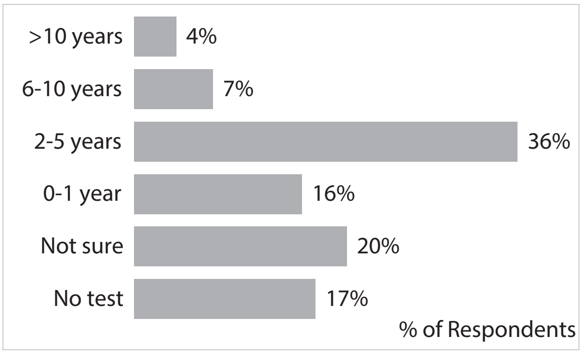

Fig. 5. The number of years since audio engineers had their last hearing test.

The hearing management strategies listed in Table 4 include monitoring and limiting audio engineer sound/noise exposure. Beyond the scope of this paper, but relevant to assessing how such exposure is managed, the survey data revealed some confusion surrounding the appropriate monitoring scale for measuring music exposure.

Ninety-seven percent of respondents said their personal hearing ability and longevity were a concern, citing their career, critical listening, and ability to mix as the main reasons, closely followed by a personal enjoyment of music, film, being a musician, and listening in general. Despite this concern, 76% of audio engineers exceeded WHO sound exposure recommendations [8] on average between one and seven times per week (Fig. 3).

2.3 Hearing Challenges That Affect Critical Listening

Ninety-one percent of audio engineers have considered the impact of any hearing impairment, while 54% report they have some hearing impairment that affects their critical listening. In assessing audio engineers' hearing, only 4% of those surveyed rated their hearing as excellent, 11% above average, and 18% as good, average, or adequate. Some respondents described their hearing as follows:

"Impaired but still accurate."

"Great compared to normal folk, ok compared to sound engineers."

"High functioning but have some damage."

"Ok for my age. I had a test last year, and I'm borderline ready for a hearing aid, but I seem to be able to hear what matters for mixing—usually, I get positive feedback on the mix and levels, including from people who would be pretty honest with me."

"Slightly impaired, but I know my curve and can compensate for it usually."

"Hearing test a couple of years ago suggested it was fairly normal, not outstanding."

". . .part of my hearing problems I solve with knowledge, I have a more trained ear than [when] I was young."

"My frequency response is far from perfect and uneven between the ears."

"Excellent, but threshold shifted."

Of the 60% of audio engineers that report hearing challenges, high-frequency loss was the most common issue, closely followed by tinnitus (Fig. 4). Those who indicated "something else" commented on asymmetric damage due to illness, "weird ear resonance," or distortion.

2.4 Hearing Tests

Some engineers recognize that hearing tests can be helpful indicators for their hearing management. Some fear that the documented results provide formal confirmation of hearing damage and the possible impact on their performance and employment. Eighty-three percent of our respondents have had hearing tests. Fig. 5 represents the amount of time since audio engineers last had their last hearing test. The 17% who had not had their hearing tested noted that they "haven't gotten around to it" or thought that testing was "unnecessary."

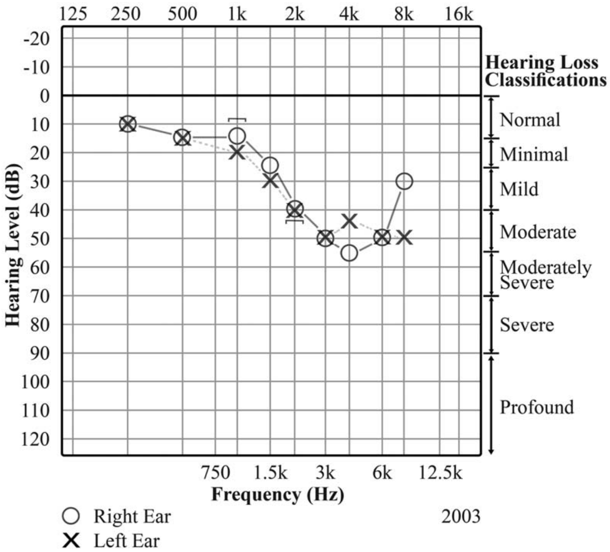

Fig. 6. Audio engineer #1 pure tone audiogram (2003).

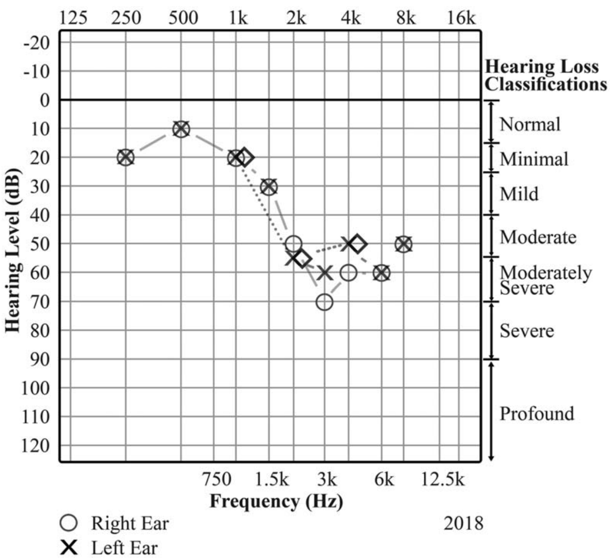

Fig. 7. Audio engineer #1 pure tone audiogram (2018).

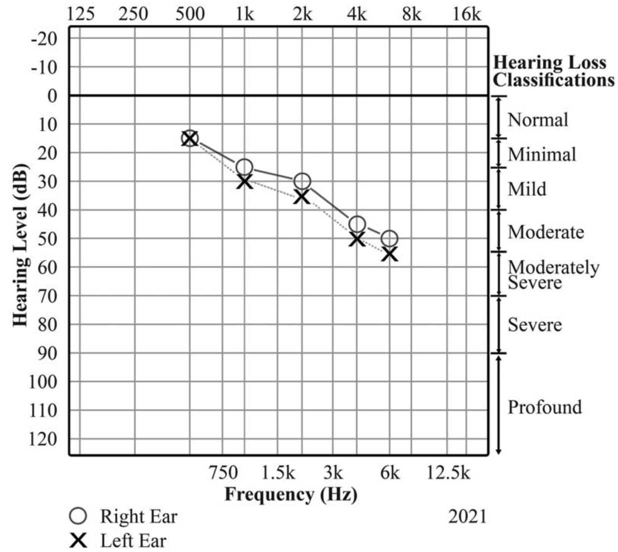

Fig. 8. Audio professional #2 pure-tone audiogram (2021).

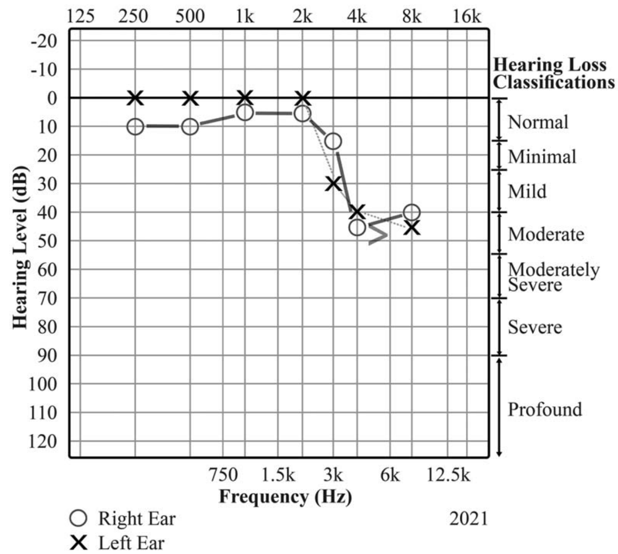

Fig. 9. Audio professional #3 pure-tone audiogram (2021).

2.5 Live-Sound Engineer Audiograms

One of our 2020 surveyed audio engineers provided audiograms from their hearing tests measured over 15 years as part of their personal hearing management. Figs. 6 and 7 are audiograms from that respondent's 2003 and 2018 pure-tone audiometric tests. Two other audio professionals (#2 and #3) provided their 2021 audiograms for this study (Figs. 8 and 9). Both audio professionals #2 and #3 had sought hearing tests after noticing hearing issues that could affect their critical listening. Publishing these results is approved on the condition of identity confidentiality.

With impaired hearing, audio professional #2 (Fig. 8) chooses to minimize their involvement in audio engineering, focusing on the business of audio. Audio professional #3 (Fig. 9) continues to be involved in audio production in which critical listening is essential. Curiously, despite a significant deficit in #3's hearing response between 3 kHz and 8 kHz, their mixes have been universally received as well-balanced without overaccented high-frequency content. Conscious, however, of the impact of hearing impairment and a recent rise in tinnitus levels, #3 has become more sensitive to audio exposure and increasingly wears hearing protection and avoids loud sounds.

2.6 Live-Sound Audio Engineer Critical Listening

One survey respondent noted in rationalizing the impact of their hearing loss:

"In general, if my hearing loss is fairly typical, it could also be that if I can make the sound clear for me, it will be clear for more people."

Far from scientifically sound, others develop philosophies to explain how they continue to work as an audio engineer with some hearing loss:

"I once heard it described as 'you learn your craft while you can hear so you can mix when you can't hear.'"

"I think that by gaining more experience within your youth, you will be able to at least set up a general idea of

what the sound should sound like. This is done by understanding the space you are in, the sound sources as well as how all the equipment is meant to work."

"I try not to over-analyse my hearing."

"I constantly strive to understand and perfect my craft so that I'll be able to still reach some level of acceptable mix should my hearing deteriorate further."

"I know what things are supposed to sound like, even if I can't hear them."

"We hear with our brains, not our ears. Reduced capability in the transducer (ear) can be overcome by retraining the brain, provided that the brain has already been trained for professional listening when the transducer is still good. Most sub-par sound is due to the engineer doing 'too much' anyway. Less is more with regard to processing live music."

2.7 Audio Engineering with Some Hearing Damage

As with audio professional #2, some audio engineers with hearing damage move into other noncritical listening employment or the business side of audio. Those engineers that continue to work as audio engineers despite some hearing damage do so, they said, through the following:

- Intentional preservation of their current hearing through hearing health checks and by wearing protection;
- Watching participant and stakeholder responses;
- Using visual tools, including real-time spectrum analyzers, sound pressure level (SPL) and console/equipment meters;
- Always having a second opinion; and
- Experience, and understanding what their damage/challenge is and working with/around it.

2.8 Other Relevant Survey Data

Two other themes are relevant for this discussion and the data analysis is summarized in this section. Subsequent publications will explore these further.

Audio engineers often have different views on when live events are considered "too loud." Even when SPLs are below legal limits, survey respondents recognized that an event could be considered "too loud":

- When participants experience physical discomfort,
- When participants are at risk of damage,
- With poor musicality from the stage performer/s,
- With a poor audio engineer's "mix,"
- When the acoustics and stage noise have a detrimental effect on the sound,
- When participants cannot hear the performer's words,
- When participants cannot hear people speaking/singing around them,
- When the level is not appropriate for the genre, content or type of event, and
- When the final sound contains undesirable distortion.

Table 5. Why audio engineers believe live-sound audiences accept "ringing" in the ears after events.

% of Respondents	Audience Beliefs on "Ringing in the Ears" After Loud Events
79%	The effects are temporary
53%	The ringing is normal when attending live events
17%	Public events are safe
18%	Something else

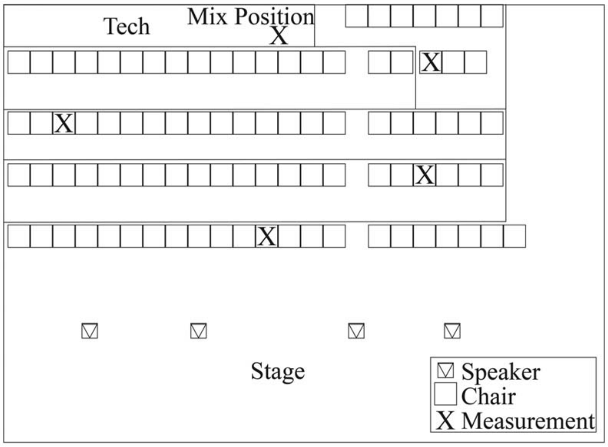

Fig. 10. A plan view of a small Christchurch theater used to test the participants' unique sonic experience.

Many live-sound participants experience "ringing in the ears" after loud concerts. Audio engineers suggest why they believe audiences accept "ringing in their ears" after a concert (Table 5).

Those that mentioned "something else" elaborated as follows:

"[Ringing in the ears is] normal but shouldn't be,"

"Bragging rights,"

"Ignorance about hearing safety,"

"[Because they] don't care about potential damage,"

"[A] sense of invincibility,"

"[They believe they are] cool."

2.9 Live-Sound Participants' Audio Experience.

In 2021, I investigated the live-sound participants' unique sonic experience within a small Christchurch, New Zealand theater shown in plan view in Fig. 10. Each side of the room was fitted with full-length heavy drapes, whereas the stage and back wall were hard wooden surfaces. Four of the same point-source speakers were hung from a ceiling truss grid and positioned as equidistantly as possible across the auditorium parallel to five rows of tiered seating. The temperature and humidity were constant during the tests.

Using pink noise through the four speakers and Rational Acoustics Smaart software, spectrum analysis and delay times were measured at the marked (X) audience positions (in Fig. 10). The time delays between the speakers to each reference microphone position were 15.33, 18.5, 20.96, 23.42, and 25.77 ms. At each of the five positions, spectrum analysis showed different audio frequency response

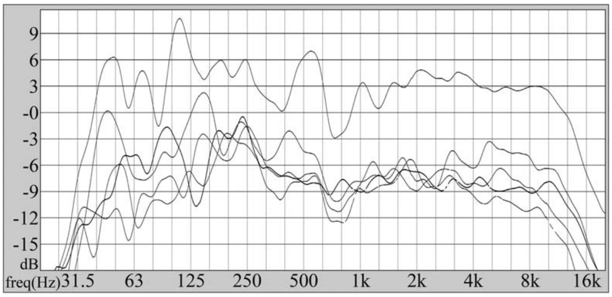

Fig. 11. Spectrum analysis from five measured positions within the small Christchurch theatre in Fig. 10.

curves (Fig. 11). The differences in delay time and frequency response at each measured location are due to the measurement location with respect to the speakers, the influence of the room acoustics, the proximity to absorbent materials, and any subtle ambient sounds present.

3 DISCUSSION

This discussion section draws themes from the collected data and compares them with other published research.

3.1 An Audio Engineer Dilemma

The personal and social benefits from the process of audio engineering can also compromise these same benefits. Focused attention on musical sounds and finding ways to describe and make sense of pitch, timing, and timbre positively impacts brain development (plasticity), multitasking, attentiveness, motor skills, timing, memory, detection of speech in noise, and reduces the occurrence or delays the onset of dementia [9–12]. Those involved in active musical activities without hearing damage may hear better than nonmusical counterparts [13]. Conductors specifically can have an exceptional ability to localize sounds [9]. In contrast, the presence of noise or a lack of meaningful sound can have a detrimental effect by "blunting" the brain, which could, in turn, hasten cognitive decline [9, 14, 15]. Nomadic people, for example, live in quiet environments and do not appear to have "great" hearing because of auditory deprivation [13].

Joiners may have "an eye" for cabinetry's detail and finish, and chefs may have a heightened taste palate. Likewise, even without superior hearing abilities, an audio engineer may be able to focus on, discriminate, and attune themselves to the various sound qualities and nuance more than non-engineers [1]. With this ability, engineers may be better equipped to affect audio balance, tone, dynamics, and spatial control; musicality; and appropriate SPL; accommodate venue acoustics and the effects of humidity and temperature; and minimize the presence of feedback and extraneous noises like cars, buzzes, insects, and coughing [1, 3]. These audio choices, however, can be affected by the audio engineer's physical, mental, and emotional condition and the presence of any fatigue or pressure.

Forty-four percent of audio engineers prepare for critical listening by referencing prerecorded tracks, 52% prepare in silence, resting their hearing, and 25% had no specific preparation routine (Table 3). With these results, we can assume that 56% of surveyed engineers consider they already have an internal sonic reference point, believing they "know" how something should sound. Although this internal reference point is valuable, any hearing impedance, impairment, or overfamiliarity may affect the alignment of this internal reference point with their mix.

Commonly, many concert SPLs exceed WHO recommendations, and an estimated 40% of people that frequently visit entertainment venues are at risk of hearing loss [8]. Precariously then, when cultural, social, and traditional pressures challenge safe practice, the benefits gained from making sense of sound are compromised by the same exposure.

In Sec. 2.2, 97% of engineers acknowledged the role their hearing plays in their career, ability to mix, and other personal activities. In other research, 87% of engineers recognize the benefits of unimpaired hearing and are aware of the risk of loud sounds [16, 17]. While acknowledging the value of optimal hearing and critical listening in mixing audio successfully, our survey revealed that audio engineers manage their hearing in different ways. Some actively and consistently prepare and manage their hearing for their role, whereas others accept the risk and any subsequent damage as part of working in a noisy industry.

There are suggestions that musicians and audio engineers may have better preparatory and reaction times to anticipate loud sounds by making the ear less sensitive and that loud impulses may be more damaging than continuous high-level sound [13]. The stapedial reflex, a natural protective mechanism within the middle ear connected to the stapes, contracts the tiny stapedius muscle in 15–20-s bursts. This reflex occurs for mid- and low-frequency high-intensity sounds [18]. Although this contraction may reduce some sound intensity, any protection is too short for extended exposure at live-sound events. Despite this and other natural protective mechanisms, the prevalence of hearing damage among most musicians and audio engineers suggests that these mechanisms are insufficient to prevent permanent damage from the amount and type of sound exposure they experience.

This study asserts that for the greatest likelihood of mixing audio in a way that fulfills an event's aims while maximizing the experience and minimizing risk, the audio engineer must mix in a similar sonic environment as other participants and be able to hear unimpeded and unimpaired.

3.2 Unique Sonic Experiences

If everyone within a venue heard and perceived sound the same way, then producing a consistent experience for all participants would be easier. Whether all participants desire the same experience is a different question and a subject for future study. Within a venue, the building acoustics, stage noise, the listener's position with respect to the speakers or sound source, and ambient sounds within the room all affect the sound vibrations that eventually reach each participant's ears [2].

The examples in SEC. 2.9 confirm that despite the same program material emanating from a source, each potential live-sound participant's ear receives unique sonic information [2, 19]. Although the temperature and humidity were constant during these measurements, changes in either would also affect the amount of time that sound would reach each listener's ears and also affect the frequency content due to changes in the absorption properties of materials within the venue [2].

Compounding the individual experience more, human physiology and the size, shape, resonant frequency, mechanical function, and hearing health of every person are also unique [18, 19]. Even with very similar hearing function, the brain may still decode, perceive, and interpret sound uniquely [19]. These sonic vibrations affect more than just the auditory system; they activate complex material interactions of human physiology, resonating in body cavities, through bone conduction, producing a sense of "touch" or causing responses in other senses [20–22].

3.2.1 Replicating Similar Sonic Spaces

Logic would assume that an audio engineer situated in a similar sonic space as most of their audience would reduce sonic variables. Live-sound "riders" frequently specify that the "mix position" must be optimal and not be under a balcony. To maximize sound uniformity throughout a venue that also flatters the program material and performs the desired psychoacoustic effect, acousticians design specific acoustic treatment solutions, and audio system engineers create "zones" with multiple speakers, array steering, and signal processing.

The "volume" level of on-stage performer instruments and foldbacks commonly affects the "front of house" mix. Depending on where event participants position themselves with respect to the stage and the "front of house" speakers, each unique participant experience will combine the stage "noise" plus the "front of house" mix plus any ambient sounds and acoustic influences. When the engineer cannot reduce the stage "noise" to achieve a balanced mix, they can feel forced to lift the overall "front of house" level more than they would rather, above the "bleed" from the stage.

Working in sonically challenging conditions, some audio engineers report they "*did the best they could*," referencing how an event sounds by walking throughout a venue with a wireless tablet and communicating with other participants. Others instead chose to protect themselves by wearing earplugs and only audio engineering in less challenging circumstances (Table 3).

3.2.2 Replicating Participant Hearing

For a "silent" concert/disco, the participants hear via headphones. Logic would suggest that to best translate a favorable audio mix to most people, the audio engineer controlling the headphone mix should also wear similar or better headphones than any of the participants. Similarly, to best translate a mix in a live-sound setting, the audio engineer should hear a similar or better audio response through unimpeded hearing without earplugs or conductive hearing loss. Without impairment, the audio engineer should have hearing equivalent or better than all other participants.

Currently, there is an imbalance between the average hearing health of audio engineers and non-engineers (SEC. 2.3). Fifty-four percent of audio engineers reported hearing issues that could affect their critical listening compared with 20% of the global population who report experiencing some hearing loss [8]. As audio engineers are more conscious of their hearing as part of their role, we could reason that they are more likely to notice the condition of their hearing health. In contrast, some may also downplay any hearing challenges as these challenges could affect work prospects. Either way, these figures demonstrate audio engineers experience over two and half times more hearing impairment than the general population. The audio engineer in (SEC. 2.6) commented,

". . . if I can make the sound clear for me, it will be clear for more people."

In this scenario, they could conceivably present a mix with more accented high-frequencies than is necessary to 80% of an audience.

3.3 Critical Listening and Impeded Hearing

Impeded or impaired hearing is when an object or process obstructs or hinders sound vibrations from being transduced or perceived by the brain in a way an audiologist would recognize as facilitating good hearing. Such impedances can be wearing earplugs or through conductive loss caused by excessive earwax, illness, or damage to hearing mechanisms. Temporarily or permanently, any impedance affects "fine aural discrimination" and compromises the audio decision-making process, a process that impacts the experience and health of all live-sound participants [16, 23, 24].

In some publications, audio engineers are encouraged to wear earplugs/hearing protection [16, 17]. Earplug effectiveness testing has measured distortion product otoacoustic emissions (DPOAEs—small sounds generated by healthy ears) and the ability of wearers to identify speech-in-noise. These tests examine outer hair cell function in the cochlea. Low levels of these emissions from the ear can indicate damage before it is apparent on an audiogram. Unfortunately, the DPOAE tests examined the effectiveness of earplugs [16, 17] well below the typical concert levels that the WHO would consider contained risk [8]. Although correctly fitted earplugs can reduce sound exposure, these DPOAE and speech-in-noise tests on the effectiveness of wearing hearing protection versus not wearing hearing protection and using musician earplugs versus standard earplugs have shown nonsignificant differences [16, 25].

Many audio engineers acknowledge that reducing sound exposure through the wearing of hearing protection is a prudent consideration when performing tasks in noisy situations that do not require critical listening skills [8]. In Table 4, 77.3% of audio engineers regularly wear hearing protection, and although not explicitly asked in our 2020 survey, 10% mentioned wearing earplugs while mixing. In other research, 18% of sound and music industry workers identified they would not wear hearing protection because earplugs or earmuffs would affect their ability to perform their job [16].

An audio engineer who wears hearing protection while exposing other people who may be less informed or less capable of making appropriate safe choices to greater risk poses an ethical conundrum. Other research described two survey participants addressing this point [16]:

"I choose not to wear protection when mixing [front of house] as I don't think it is responsible to subject your audience to a mix I consider dangerously loud."

"I never (or hardly ever) wear hearing protection when mixing because it is my responsibility to keep levels unharming for the audience. So, if I can't hear how loud it is, that is like not caring."

Earplugs or earmuffs protect only the wearer. Correctly fitted, non-musician earplugs will attenuate higher frequencies more than lower frequencies because of wavelength size and occlusion [18]. Musician earplugs may be capable of "flat" attenuation and reducing occlusion effects [18, 26]. Although a flat attenuation may be desirable on paper, the ear perceives audio frequencies differently depending on their SPL, as demonstrated by equal loudness curves [27]. Flat attenuation may not be ideal for critical listening [28]. Earplugs without compensation for changes in frequency perception at varying SPLs could compromise how an audio engineer makes sense of a sound and, therefore, how they mix. Blocking the audio engineer's ear canal adds another perceptual variation between the audio engineer and other live-sound participants.

3.4 Critical Listening and Impaired Hearing

Impaired hearing with a permanent reduction in ear sensitivity caused by noise has become the most common worldwide occupational disease [13]. As sound exposure tolerance varies between people, risk calculations can only indicate the likelihood of hearing impairment due to sound exposure. Noise standard specifications balance an accepted risk against the financial and social costs to implement [29]. There is clear evidence that the audio engineer's personal sound exposure poses a significant danger to their hearing [17].

Within audio reinforcement systems or in engineer hearing, should any interconnecting part be compromised through wear and tear, overuse, or exceeding the recommended specification, then damage can occur, and the final "sound" and the participant experience are compromised. In SEC. 2.3, respondents believed that any hearing impairment they had did not appear to impact their audio engineering negatively. Still, any impairment must introduce and increase variables into critical listening. More than just affecting the assessment of musical properties, the audio engineer's hearing health can affect their focus, communication, cognitive ability, finances, employment, and mental and physical well-being [8].

In the context of audio engineering, hearing damage can [30–32]

- Affect a person's sensitivity to, and perception of, some audio frequencies;
- Cause a person to hear a noise not generated outside of the ear (tinnitus);
- Reduce dynamic range tolerance (recruitment);
- Introduce a hypersensitivity to sound levels (hyperacusis);
- Cause the perception of multiple tones when only one tone is played (diplacusis);
- Cause tone distortions from "dead regions" in the frequency range, producing responses that are noise-like without a clear pitch;
- Reduce the ability to perceive a sound's fine time structure due to synchronization between the sound and when the nerves "fire";
- Reduce pitch perception;
- Reduce a person's ability to interpret some sounds among other sounds, like speech within noise; and
- Reduce a person's ability to locate a sound's direction.

Any live-sound exposure calculations should also factor in the average exposure from sound sources away from the event. Some research has suggested that short, powerful acoustic impulses close to the ear, such as plugging or unplugging phantom power devices while monitoring on headphones, can cause more hearing damage than continuous noise [13].

3.4.1 Temporarily Impaired Hearing for Critical Listening

Overexposure to sound can cause a temporary threshold shift (TTS) that affects audio frequency discrimination [33]. Some audio engineers may refer to TTS as hearing fatigue [34]. One publication suggests TTS may be a positive mechanism that reduces hearing sensitivity to help avoid a permanent threshold shift (PTS) [13]. Another publication suggests TTS may be a precursor to PTS [18]. Although some individuals may seem to recover from TTS, damage may be "hidden" from audiometric testing results due to cochlea synaptopathy, where damage to neural function can affect the ability to understand speech or other audio signals in noise [14, 35, 36].

Some mechanisms within the ear may tolerate more significant levels of music than noise. This tolerance can be due to differences in spectral content, transient variations, or if the content is favorable or not. Because of this tolerance, the potentially more dangerous stimuli can be the least bothersome [23, 37–39]. Unpleasant sound/noise can be a psychosocial nonspecific stressor that arouses the autonomous nervous and endocrine systems, threatening homeostatic bodily systems [23]. Apart from physical discomfort, survey respondents in SEC. 2.8 noted that an audio "mix" might be perceived as unpleasant or "loud" if the musicality on stage, or the audio engineer's mix of levels or spectral content, is poor. Other respondents noted an event would be "too loud" if participants cannot hear the words, or if the mix contains undesirable distortion. These descriptors im-

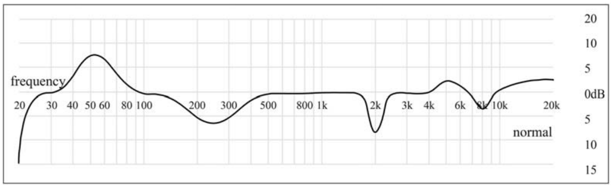

Fig. 12. An example parametric equalizer curve inserted on a sound source, in which tonal adjustments are within 10 dB of any given frequency band.

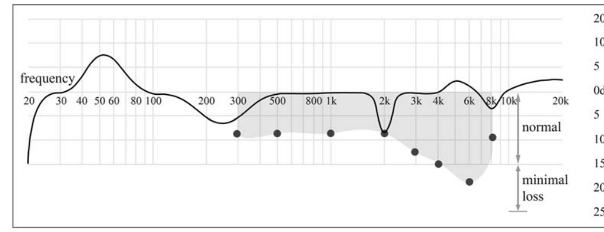

Fig. 13. The pure-tone testing responses averaged from 69 pop musicians, four disc jockeys, four managers, and six live-sound engineers [40] overlaid on Fig 12.

ply that a well-balanced, pleasant mix on a high-quality sound system may not feel as loud as it is, producing a potentially more dangerous stimulus.

3.4.2 Permanently Impaired Hearing for Critical Listening

While 54% of our participants reported experiencing hearing damage that could affect critical listening (SEC. 2.3), another study has found that 68% of their music industry sample experienced hearing damage [16]. Assessing how well an audio engineer with hearing damage can mix may be a subjective exercise. Musicianship, equipment quality, venue acoustics, temperature and humidity, audio engineer knowledge, skill, focus, musicality, and pressure from other stakeholders and peers all play a part in the resultant audio mix. We can instead explore how various hearing conditions may affect critical listening and thereby an audio mix.

3.4.3 Frequency Discrimination

For the live-sound audio engineer, whose decisions affect the experience and the health and well-being of others, a reduction in the ability to discriminate and then fine-tune audio frequencies increases the variables in producing a pleasing and cohesive mix. Inner ear hair cell damage can reduce an audio engineer's audio frequency perception [8]. Some high-frequency loss could be regarded by some as temporary (TTS). Some may be age-related (presbycusis), and some may be the permanent result of exposure to loud sounds. Whatever the engineer's hearing response, their audio perception across the audio frequency spectrum will inform and influence their decision-making.

Fig. 12 is an example parametric equalizer curve inserted on a sound source. The vertical scale is in decibels (dBs), and the horizontal scale is audio frequency measured in hertz. Note that in this example, each frequency gain or reduction is within 8 dB. To describe the effect of these tonal adjustments in words is to

- Roll-off low sub frequency below 25 Hz,
- Boost "thump" at 50–64 Hz by 7 dB,
- Reduce muddiness at 250 Hz by 6 dB,
- Reduce a nasal sound at 2 kHz by 8 dB,
- Add sibilant clarity at 5 kHz by 2.5 dB,
- Reduce harshness at 8 kHz by 3 dB, and
- Add "air" and "sizzle" above 12 kHz by 2 dB.

Thirty-two percent of surveyed audio engineers report experiencing a loss of high-frequency perception (Fig. 4). Along with a decibel reading, various categories describe the severity of their loss, in which some people may consider the terms "minimal" or "mild" hearing loss [24] an acceptable level of personal impairment.

In a form recognized by audio engineers, the images in Figs. 13–16 represent pure-tone audiometric response measurements displayed over the parametric equalizer in Fig. 12. The black dots average the left and right ear responses, and the shading indicates the area where hearing loss compromises precise audio frequency and level discrimination.

Lindgren and Axelsson published an audiogram that averaged the pure-tone hearing responses of 69 pop musicians, four disc jockeys, four managers, and six live-sound engineers [40]. Fig. 13 displays these results overlaid on the parametric equalizer from Fig. 12.

The loss in frequency response perception demonstrated in Fig. 13 is considered "normal" or "minimal" and exceeds the fine adjustments made in the equalizer example. Although skilled audio engineers often manipulate tonal controls in single decibel increments, engineers with losses shown in Fig. 13 with a 10–20-dB loss around 6 kHz will perceive these levels at half to a quarter of the loudness of those engineers without impairment [2]. Compromised audio frequency perception around 4–6 kHz, where sibilance and clarity are affected, could lead an engineer to overcompensate any tonal modifications producing an overly "bright" or "harsh" mix. Fig. 14 represents the audio engineer #1 audiogram from Fig. 7 overlaid on Fig. 12.

The 2003 audiogram in Fig. 6 describes audio engineer #1's hearing loss as "moderate" on the threshold of "moderately severe." Their 2018 audiogram in Fig. 7 and the parametric equalization representation in Fig 14. reassesses and reclassifies their loss as "moderately severe" on the threshold of "severe" [24]. Although "minimal," "mild," or "moderate" descriptors may not sound as serious to an audio engineer as "severe" or "profound" loss, we see in Figs. 13–16 that any loss must affect critical listening and thereby affect incremental tonal adjustments.

For frequencies above 500 Hz, a reduction of 10 dB halves the perceived loudness of those affected frequencies [2]. Therefore, a 50-dB hearing loss around 4 kHz potentially represents 1/32nd (3.1%) of the perceived loudness of those frequencies as perceived by someone without damage.

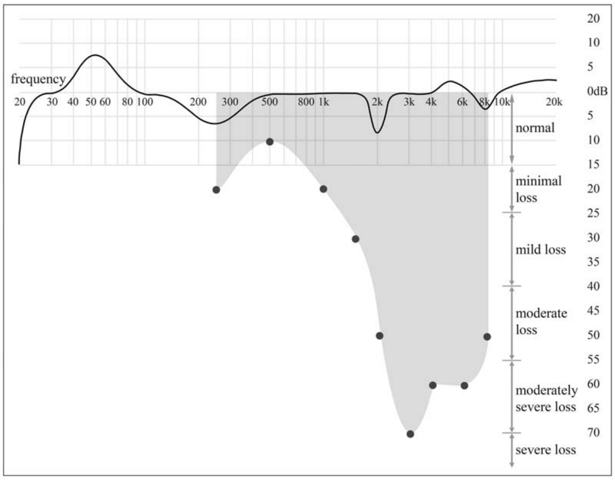

Fig. 14. The 2018 audio engineer #1 audiogram results from Fig. 10 overlaid on the parametric equalizer from Fig. 12.

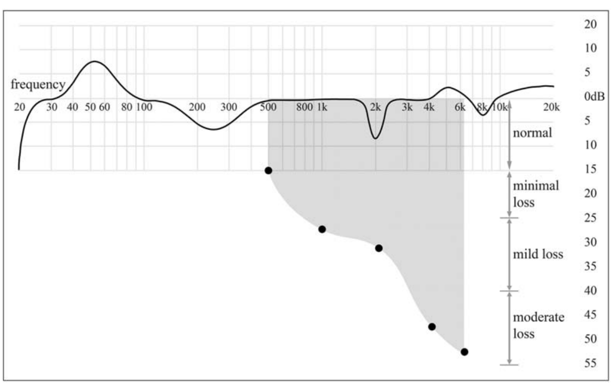

Fig. 15. The 2021 audio professional #1 audiogram results from Fig. 8 overlaid on the parametric equalizer from Fig. 12.

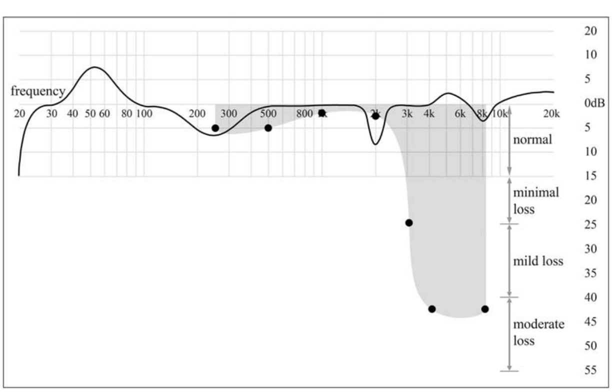

Fig. 16. The 2021 audio professional #2 audiogram results from Fig. 9 overlaid on the parametric equalizer from Fig. 12.

Figs. 15 and 16 are parametric equalizer representations of audio professionals #2's and #3's 2021 pure-tone audiograms from Figs. 8 and 9, respectively. As in SEC. 2.5, both audio professionals had sought hearing tests after noticing hearing issues that could affect their critical listening. Publishing these results is approved on the condition of identity confidentiality.

Audio professional #2 (Figs. 8 and 15) chooses to minimize their involvement in audio engineering and now focuses more on the business side of audio. Audio professional #3 (Figs. 9 and 16) continues to be involved in audio areas in which critical listening is required. Curiously, despite a significant deficit in their hearing response between 3 kHz and 8 kHz, their mixes have been universally received as well-balanced without over-accented high-frequency content. However, conscious of the impact of hearing impairment and a recent rise in tinnitus levels, #3 has become more sensitive to audio exposure and wears protection more frequently and avoids loud sounds.

Any damage to audio frequency perception increases the variables in producing a cohesive and pleasing mix. Reductions in frequency response could also affect an audio engineer's perception of audio feedback, radio interference, or speech detection in noise. Although some audio engineers with high-frequency loss have the potential to increase tones they perceive to be low, some, it seems, have found ways to still present mixes that could be regarded as well-balanced. We can surmise that high-frequency loss among some audio engineers may indicate why many live-sound concerts contain significant high-frequency content. However, hearing damage alone may not be a conclusive indicator of whether an audio engineer is capable of producing a balanced and pleasing mix.

3.4.4 Tinnitus

Tinnitus is the perception of noise not generated outside the body [24, 41, 42]. Tinnitus can result from severe hair cell damage caused by excessive noise or from other unrelated factors [13]. Two-thirds of sufferers experience tinnitus brought about by medical problems within the head and neck or other psychological concerns [13].

Thirty-one percent of the surveyed audio engineers report experiencing tinnitus (Fig. 4), compared with other recent studies in which 81% of audio engineers report experiencing tinnitus during or after work. Forty-nine percent of sufferers cite music as the trigger with the onset related to the exposure from live-sound concerts [17]. Comparatively, 50% of professional musicians report experiencing tinnitus, which is double the occurrence in the general population [30, 34].

For the audio engineer, the increased noise floor caused by tinnitus masks a range of audio frequencies. We can assume that at concert SPLs, the effects of tinnitus may be significantly less or negligible. Tinnitus can mask equipment hums, buzzes, radio frequency interference, and audio feedback at quieter levels. Other studies have found 84.7% of concert-goers experience tinnitus afterward [43]. Many of our audio engineer respondents believed that concert-goers accept "ringing in the ears" as expected, normal, or temporary (SEC. 2.7). Some of the surveyed audio engineers hold this same belief about their own tinnitus.

3.4.5 Recruitment

Recruitment is a reduced tolerance to dynamic range [30]. Within the cochlear, sensorineural hearing loss reduces the sensitivity to low-intensity sounds but may have little effect on high-intensity sounds [24]. Recruitment may not then affect an audio engineer's performance in many concert situations where the dynamic range is narrow and the SPL is high. When a broader dynamic range is favorable, as in theater, conferences, churches, and orchestral music, recruitment may drive an engineer to control and reduce the dynamic range more than is necessary, particularly with more subtle and low-intensity levels.

3.4.6 Hyperacusis

Hyperacusis is an abnormal hypersensitivity to sounds that are tolerable to others [24, 30, 41]. Different studies have reported that between 30–79% of musicians experience this condition, compared with 15% of the general population [30]. Depending on the severity of hyperacusis, the reduction in audio engineer tolerance to audio levels that are acceptable to others can affect their objectivity, audio choices, musical enjoyment, career, social interactions, and well-being.

3.4.7 Diplacusis

Diplacusis is a condition in which different tones are perceived in separate ears when only one tone is present [24, 30, 41]. Diplacusis is present in 18% of musicians and reported by 2% of surveyed audio engineers (Fig. 4). Depending on the variance, an audio engineer with diplacusis may perceive dissonance where there is none, find tuning a challenge, and make the perception of a well-blended mix difficult.

3.4.8 Other Hearing Conditions

Damage to neural fibers, impaired figure-ground perception (difficulty distinguishing sources of interest from background sounds), and sensorineural hearing loss affect audio perception and discrimination even though a pure-tone audiogram may show no physical damage to hearing mechanisms. These conditions can reduce a person's ability to interpret some sounds among other sounds, like speech within noise, or for sound localization [30, 32]. Despite the benefits gained in the active participation of making sense of sound, 22% of our surveyed engineers noted challenges related to understanding speech-in-noise (Fig. 4).

3.5 Critical Listening with Some Hearing Damage

In SEC. 2.6, audio engineers rationalized how they believe the negative impact of their hearing damage to be minimal. Some described continuing to work as an audio engineer by

- Intentional preservation of their current hearing through hearing health checks and by wearing protection;
- Using visual tools, including real-time spectrum analyzers, SPL and console/equipment meters;
- Experience, and understanding what their damage/challenge is and working with/around it;
- Always having a second opinion; and
- Watching participant and stakeholder responses.

Despite the subjectivity in assessing an engineer's ability to mix, although they have some hearing issues, there is evidence to show that some musicians and engineers may still have higher frequency discrimination than non-musicians, and the brain may be able to fill in some "blanks." The perceived timbre of a sound combines a fundamental frequency with harmonics and partials [2]. The louder the sound, the more audible, the quieter harmonics become. Any loss in frequency perception must also affect the perceived timbre. Other research has suggested that a missing fundamental can be "heard" when the brain extrapolates harmonics [11, 44]. Despite the missing fundamental now being "heard," the harmonic balance may still be perceived differently from those without damage.

3.6 Hearing Management and Hearing Tests

Sixty-four percent of audio engineers in Table 4 said they monitor their exposure, 74% said they limit their exposure, and 52% prepare their ears by silence and rest. Beyond the scope of this paper, but relevant to how audio engineers manage their sound exposure, our survey data revealed a lot of confusion surrounding the appropriate monitoring scale for measuring their exposure to music. Although the hearing management processes mentioned have value, the level of damage experienced by most audio engineers suggests they could improve their management processes.

Also, beyond the scope of this paper, but worth a brief note here, is that some low-level noise can cause permanent damage to the auditory nervous system—the hearing brain—as it tries to extract meaning. Such damage may disrupt some of the connections between the hair cells and the "higher" brain areas, where some of the links that carry important information like speech are missing [14].

With 83% of those surveyed having had hearing tests, the respondents recognize that these tests can be helpful for their hearing management (Fig. 5). Others who had not had hearing checks "hadn't gotten around to it" or thought testing was unnecessary. Some engineers fear a formal confirmation of damage and the possible impact on their performance and employment. Although standard hearing tests may be indicators of the presence of damage, they may not definitively predict how an audio engineer will perform. The most common methods for testing hearing function are pure-tone testing and DPOAE testing.

3.6.1 Pure-Tone and DPOAE Testing

Most audiologists would point to pure-tone audiometric testing as the most significant "gold standard" indicator of music-induced hearing loss. Pure-tone audiometric testing investigates hearing responses using single audio frequency tones at various low SPLs.

Unfortunately, pure-tone testing alone cannot conclusively determine how well an audio engineer can mix at concert levels. At concert levels, frequency perception differs from the perception of frequencies at low-level audiometric testing. The equal loudness contours demonstrate these differences [27]. Also, as SPLs increase, the audibility of more harmonics and partials increase [2, 11, 44]. As in SEC. 3.4.5, sensorineural hearing loss can reduce the sensitivity of low-intensity sound but may only have a minor effect on high-intensity sound [22], once again providing less impact on concert-level mixing. For those with tinnitus, an increased noise floor can mask low-level frequency tones that impact pure-tone test results. As not all tinnitus is the result of damaged hair cells, pure-tone audiometric tests may not be a conclusive indicator of noise or music-induced hair-cell damage [45]. DPOAE tests, instead, can indicate damage to cochlear outer-hair-cell function by measuring small sounds generated by healthy ears [46].

3.6.2 Annoyance as Hearing Test Method

Some research has tested hearing using pure-tone annoyance thresholds as indicators of damage [17]. Such tests with audio engineers may also not be conclusive. The experienced engineer develops an understanding of how simple audio frequencies make up complex sounds. Some frequencies are more noticeable or problematic than others, such as a 2-kHz nasal tone, 5-kHz sibilance, 6.3-kHz feedback frequency, boxiness around 800 Hz, and 250-Hz "warmth" or "mud" sound. As mentioned in SEC. 3.4.1, a well-mixed song on a good sound system may sound less "loud" and potentially less annoying than a poor mix with poor frequency balance or from a poor sound system at the same SPL. Likewise, a single-frequency tone will sound more annoying by itself than when mixed with other sounds by a skilled, unimpeded, and unimpaired audio engineer with excellent critical listening skills.

3.7 Education

There are suggestions that auditory damage mainly results from ignorance about the problem than in places where noise levels are the highest [13]. Most of our surveyed audio engineers recognize their hearing as their most valuable critical listening tool (SEC. 2.2), are generally aware of the hearing risk in live-sound activities, and are open to learning and acting on hearing management strategies.

Many publications and marketing campaigns focus on the damage loud sounds can cause. With damage to audio engineers' and musicians' hearing being at least two and a half times greater than the general population, we should reassess our hearing management education strategies. Although beyond the scope of this paper, a positive approach promoting the benefits of hearing management on critical listening, audio assessment and audio manipulation, career, long-term health, and well-being may be received better than warnings and scare tactics. Axelsson [47] echoes these recommendations:

"The comparatively poor results of our warnings and scare tactics should be recognized and accepted. It would probably be better to try to influence young people to appreciate their wonderful sense of hearing" [47].

4 CONCLUSIONS

Critical listening is an essential audio engineer tool for judicious audio assessment. Audio engineers regularly work in environments that challenge critical listening ability and hearing longevity. To have the greatest likelihood of translating an audio mix to others in a pleasing way that fulfills the event's aims, the engineer needs to reference how their mix should sound. They should also reference how other participants experience the sound by listening in a similar sonic space with an equal or better, unimpeded, and unimpaired hearing.

For each live-sound participant, the "experience" can provide physical, emotional, and social benefits. Alongside employment, the audio engineer's "making sense of sound" also offers many health benefits. If their sound exposure exceeds their unique hearing tolerance mechanisms, the same experience can compromise these benefits. Audio engineer hearing impairment not only affects their own health and well-being but, along with any impedance, also increases the variables in translating an audio mix to an audience. The frequency content, level, balance, spatial choices, and pleasantness of a mix then impact an audience's "experience," health, and well-being.

Hearing impairment from music and leisure activities is increasing among the general worldwide population, and live-sound musicians and audio engineers experience more than twice the occurrence of hearing damage. Although hearing tests may not conclusively determine the potential quality of an audio engineer's performance, many audio engineers with impaired or impeded hearing continue to mix, believing that these will not negatively impact their audio decision-making. The hearing management processes that many currently follow seem insufficient to monitor, prevent, and quantify the impact of hearing damage.

In protecting the "live-sound experience" by not addressing the impact of high sound exposure, the live-sound industry may also be damaging the "experience." Responsibly, the live-sound industry should reassess how they protect their staff and those participants who may be uninformed or incapable of protecting themselves. Further research may even find that by providing safe options at events and by lowering the average SPL that the "experience" and ticket sales improve.

Current hearing management education and marketing focus on the dangers of loud sounds and does not seem to improve hearing health among musicians and live-sound engineers. Instead, a different education and marketing approach could focus on the benefits of hearing health and longevity while also investigating options that allow live-sound participants respite without damaging the "experience."

Along with training, skill, and experience, an audio engineer's unimpeded hearing for critical listening provides the greatest likelihood of translating and predicting a mix that appeals to and is conducive to the responsible care for the health and well-being of all participants, whatever their hearing ability or location within a venue.

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Stephen Compton is a Music Technician and Lecturer with the University of Canterbury and freelances as a live-sound engineer/sound designer and AV recording and post-production engineer. He has been a former event coordinator, foreman/builder, guitar teacher, band member, music director, and full-time live-sound tech/engineer. Stephen has mixed thousands of large and small-scale events, engineered/sound designed 72 seasons of music theater, and on one occasion, was even a guitar tech for 10cc. Over the years, Stephen has conducted many training sessions with volunteer audio engineers and since 2018 has adjusted his focus to promote the benefits of hearing care to audio engineers and musicians. After achieving his Master’s degree in 2016, he is now a Ph.D. candidate investigating live sound culture, audio engineer choice, and managing hearing in a traditionally loud environment.