PRECISION VS. PROTECTION: A COMPARATIVE STUDY OF METRONOME DEVICES ON TEMPORAL ACCURACY AND SOUND EXPOSURE RISKS FOR DRUMMERS IN LIVE MUSIC

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1 INTRODUCTION

The need for this research stems from growing concerns over the long-term effects of sound exposure on musicians. In-ear monitors (IEMs) and click tracks, while essential for precision in live and studio performances, often require high sound levels to be effective, exacerbating the risk of noise-induced hearing loss (NIHL).

This small-scale study will find out if there are ways to reduce NIHL in musicians, specifically drummers, whilst maintaining the precise performance timing and analysing the user comfort levels. Current alternatives, such as visual or haptic metronome systems, may offer safer solutions, but their impact on timing accuracy remains underexplored. Thus, there is a pressing need to evaluate whether these alternatives can preserve performance quality while reducing risk to auditory health.

2 NOISE-INDUCED HEARING LOSS

NIHL is a sensorineural condition resulting from prolonged exposure to high sound pressure levels, causing irreversible damage to cochlear hair cells (Ding, Yan, & Liu, 2019[1]). While occupational exposure is well studied, recreational noise, particularly in music, has become a critical concern (Clark, 1991[2]). Genetic susceptibility also plays a role, with research on cochlear changes and transcriptomic shifts suggesting potential for targeted therapies (Konings, Laer, & Camp, 2009[3]; Early et al., 2022[4]).

Despite the risks, musicians often show low awareness and poor adoption of protective measures. Studies highlight widespread exposure to hazardous levels across genres, with up to 60% experiencing hearing-related issues such as tinnitus and NIHL (Ciorba et al., 2012[5]; Sliwinska-Kowalska & Zaborowski, 2017[6]). While custom earplugs and in-ear monitors reduce risk (Barker et al., 2017[7]), concerns about sound quality and limited education remain barriers (Ziegler et al., 2018[8]; Münster et al., 2020[9]).

2.1 Metronome Use in Drumming

Metronomes are key for developing rhythmic accuracy, yet their effectiveness is debated. Auditory cues are generally the most effective for maintaining tempo (Sowiński & Dalla Bella[10], 2013; Einarson & Trainor, 2016[11]), but over-reliance may inhibit an internal sense of pulse (Paydarfar et al., 2017[12]). Neurocognitive studies confirm that trained percussionists can sustain tempo without external aids (Hove et al., 2024[13]).

Research also highlights the importance of microtiming variations in musical feel, suggesting strict metronomic timing can limit expression (Hellmer & Madison, 2017[14]). Monitoring choice further impacts musical outcomes, with differences reported between in-ear and loudspeaker systems (Berg et al., 2017[15]).

2.2 Multisensory Feedback in Music Performance (Haptics and Visual Aid)

Emerging technologies explore how multisensory cues can support timing while reducing auditory strain. Haptic feedback, converting sound into tactile stimuli, offers discreet alternatives for metronome use and sensory substitution, benefitting both musicians and hearing-impaired individuals (Remache-Vinueza et al., 2021[16]; DeGuglielmo et al., 2021[17]). Fully integrated haptic feedback has been shown to improve timing precision and expressivity (Young et al., 2017[18]; Yoshida et al., 2023[19]).

Haptic technology provides discreet, body-applied feedback that can substitute or augment auditory cues, reducing sound exposure for musicians and supporting those with hearing impairments (Flores Ramones & del-Rio-Guerra, 2023[20]). Applications such as haptic music players (Remache-Vinueza et al., 2021[16]) and wearable devices converting sound into tactile signals (DeGuglielmo et al., 2021[17]) demonstrate potential for both performance enhancement and sensory substitution, though refinement is required. These developments highlight haptics as a promising alternative to traditional metronome systems.

Visual cues play a critical role in enhancing timing and synchronisation by influencing temporal perception and facilitating gestural coordination within ensembles. Research underscores the significance of body movements and conductor gestures in anticipating tempo (Bishop et al., 2019[21]; Colley et al., 2018[22]). Furthermore, recent technological advancements, such as the “Audeo” system that converts hand movements into audio output, demonstrate the potential of visual information to improve synchronisation and extend the boundaries of musical performance (Su, Liu, & Shlizerman, 2020[23]; Chebat et al., 1993[24]).

2.3 Human Response to Haptic Feedback

Although auditory stimuli yield the fastest reaction times, haptic responses remain effective, particularly when combined with other modalities (Teichner, 1954[25]; Yoshida et al., 2023[19]). Studies show musicians perform best with fully haptic feedback, which improves timing, expressivity, and user preference (Young et al., 2017[18]; Young, Murphy & Weeter, 2020[26]). Haptic cues also enhance immersion in VR concerts (Lee et al., 2023[27]), confirming their value in performance and audience engagement.

2.4 Human Perception of Tactile and Visual Cues in Timing Tasks

Timing perception depends on multisensory integration, with vision often dominating tactile inputs (Ernst & Banks, 2002[28]). Visual cues can bias tactile judgments (López-Moliner & Soto-Faraco, 2007[29]), while cross-modal effects such as simultaneity sensitivity (Harrar & Harris, 2005[30]), the kappa effect (Sarrazin et al., 2004[31]), and motion-induced time dilation (Kanai et al., 2011[32]) illustrate the complexity of sensory interaction. These findings emphasise the potential of integrating tactile and visual cues to improve temporal precision in musical performance, particularly for sensory-impaired musicians.

3 EXPERIMENTATION AND RESULTS ANALYSIS

This section outlines the experimental procedure used to compare different metronome methods and their effect on drummers’ timing precision and preference.

3.1 Hypothesis

It is hypothesised that combining a reduced-SPL auditory click track with either haptic feedback via a ButtKicker or a visual light pulse will allow drummers to maintain timing precision while reducing sound exposure, thereby mitigating the risk of NIHL. Traditional click tracks often require high IEM levels, increasing exposure to potentially harmful sound. Integrating alternative sensory feedback may provide a feasible strategy for hearing conservation without compromising performance.

3.2 Pilot Experiment

A pilot study was conducted to validate the experimental setup, including the use of auditory, visual, and haptic metronomes, as well as the accuracy of timing and SPL measurements. The pilot confirmed that the methodology was robust, comfortable for participants, and suitable for the main experiment, with only minor adjustments needed for example, optimising butt-kicker placement.

3.3 Main Experiment

3.3.1 Aims and Method

The main experiment evaluated whether multimodal metronome methods could reduce required SPL for IEMs without compromising timing precision. Participants performed a standardised groove under six conditions: click-track only, light only, haptic only, click-track + light, click-track + haptic, and light + haptic. Timing deviations were measured via Logic Pro (in milliseconds), SPL monitored with the 10EaZy system, and subjective feedback collected via post-condition questionnaires. The experimental environment replicated a typical rehearsal setting to maintain ecological validity. Metronome order was randomised, and post-trial surveys and interviews assessed usability and perception. Figure 1 below shows the set-up for experimentation.

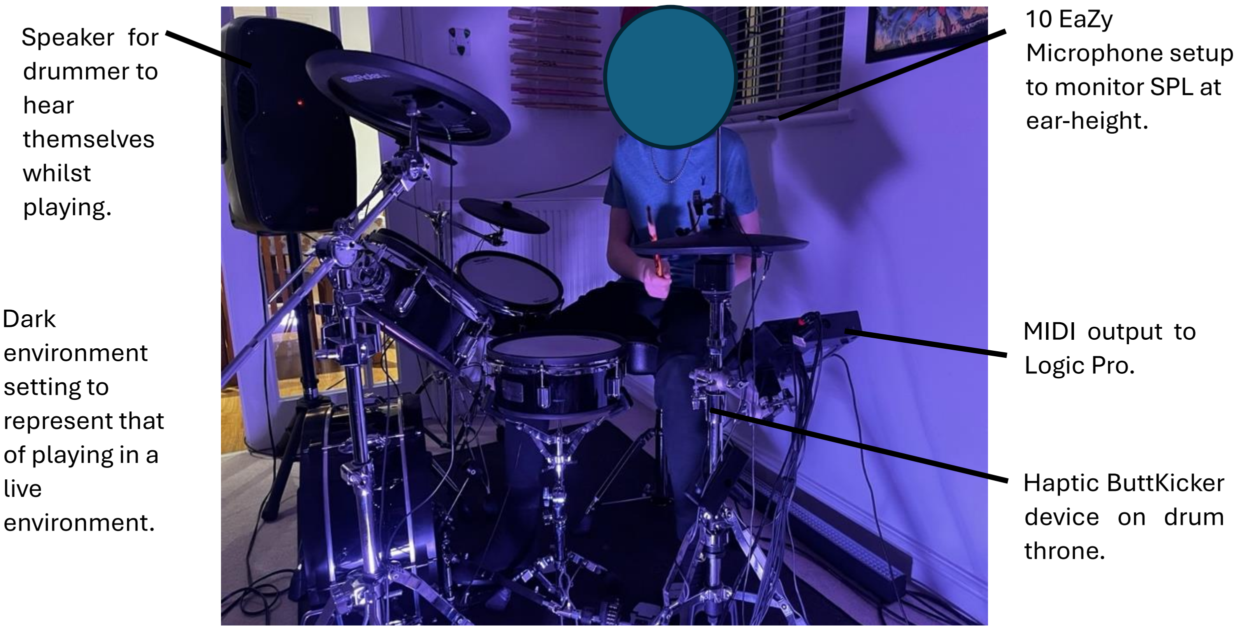

Figure 1 Experiment in progress, Participant drumming to given beat using the combination method of in-ear click combined with haptic feedback from the ButtKicker

3.3.2 Experiment Results and Analysis

	Metronome Method	**Timing Precision (%)**					
Participant Number		**1**	**2**	**3**	**4**	**5**	**6**
Level of Drumming		Professional	Professional	Beginner	Advanced	Advanced	Advanced
	Click track ONLY	99.72	99.31	85.12	94.4	92.89	96.5
	Light ONLY	86	84.22	72.45	86.1	75.57	84.33
	Haptic ONLY	98.3	96.4	69.2	87.88	72.49	80.75
	Click track and Light	96.38	94.78	84.4	90.21	84.1	89.92
	Click track and Haptic	98.61	97.95	85.78	93	83.2	86.6
	Light and Haptic	85.22	87.33	75.1	89.23	71.71	83.89

Table 1 A Table presenting the calculated timing precision as percentages for each participant compared to their Skill Level

The 6 participants from this experimentation ranged from beginner drummers who have never experienced playing with a metronome, through to professional drummers who have played in the industry for years.

Timing precision was highest with click-track-only conditions, particularly for professional drummers. Light-only and haptic-only conditions reduced accuracy for less experienced participants. Combined methods allowed lower SPL while maintaining relatively high timing accuracy. Table 1 presents participant performance across conditions. Timing deviation was measured in milliseconds from the reference tempo (120 BPM) in Logic Pro across the six tested metronome conditions. The mean absolute deviation and standard deviation were calculated for each participant and condition. Quantitative data were analysed using mean and standard deviation of onset deviations to assess timing accuracy across metronome conditions. SPL levels were averaged and compared to NIOSH and ISO 1999 safety thresholds. Qualitative data were thematically analysed (Braun & Clarke, 2006[33]) to identify patterns across metronome types and experience levels.

3.3.3 Experiment Timing Precision Results

Timing precision was assessed by analysing the recordings from the drummers using an electronic drum kit into Logic Pro, with MIDI data capturing the exact timing of each drum hit. Precision was calculated by looking at the bass drum information and comparing these hits against a reference 120 BPM metronome, measuring deviations from the expected timing.

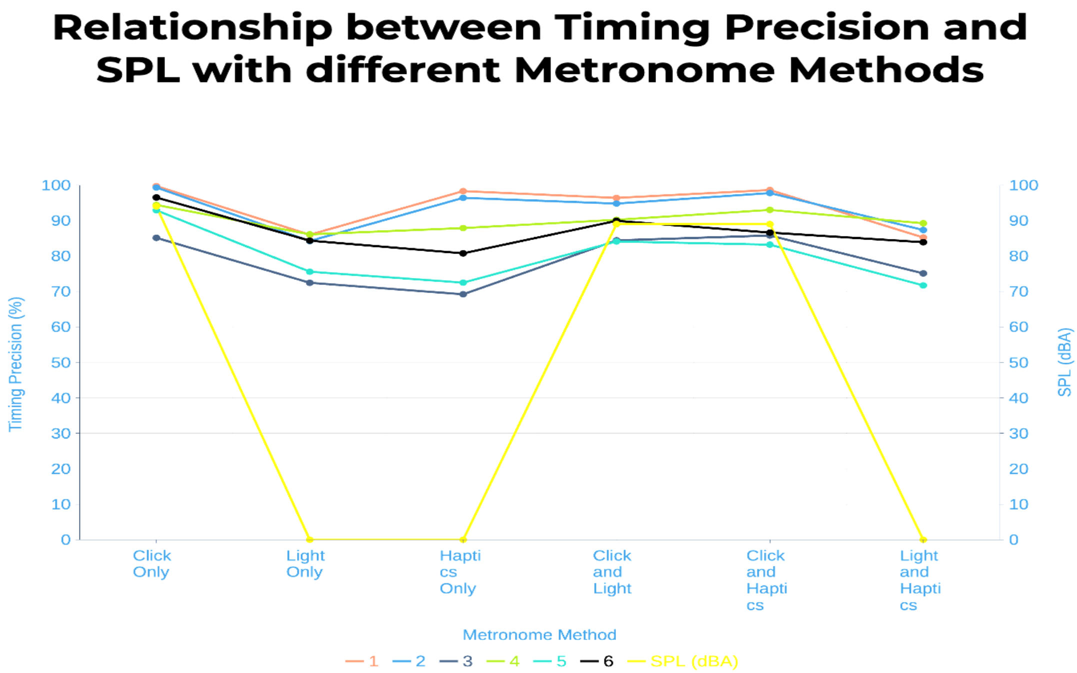

Figure 2 A Graph to show the Relationship between Timing Precision and SPL with different Metronome Methods highlighting the deviation in accuracy due to lower SPL levels

Figure 2 presents the relationship between timing precision and SPL across six metronome methods, revealing clear patterns in the effectiveness of different sensory modalities. Methods incorporating auditory cues, particularly the Click Only condition, consistently produced the highest timing precision, with all participants performing above 90%. This reinforces the dominant role of auditory input in temporal coordination. In contrast, the Light Only and Haptics Only conditions resulted in markedly lower precision, with some participants falling below 75%, indicating that unimodal visual or tactile cues are less effective for rhythm synchronisation.

Multimodal combinations such as Click and Haptics or Click and Light restored performance to levels close to the Click Only condition. These results indicate that sensory integration enhances temporal accuracy through cross-modal facilitation, improving performance while reducing auditory exposure.
SPL data showed a clear trade-off. Click-based methods produced the highest SPLs, whereas non-auditory methods registered 0 dBA, eliminating acoustic output. Although Light and Haptics are suitable for noise-sensitive settings, their reduced timing precision limits practical use. Auditory metronomes remain the most accurate, but combining haptic cues with low-volume auditory input (89 dBA) offers an effective balance between performance quality and hearing protection.

Professional drummers achieved the highest accuracy with Click Only and Click and Haptics, the latter maintaining precision with reduced SPL. The beginner drummer performed best with Click and Haptics, while non-auditory cues alone were least effective.

Overall, haptic feedback provides a viable, safer alternative to click tracks, preserving timing accuracy while reducing sound exposure. Although Light Only proved less effective, it may support hybrid systems designed to enhance rhythmic precision in sound-sensitive environments.

3.4.1 Perceived Timing Precision Across Metronome Methods

Participants in the experiment were exposed to different metronome modalities and were subsequently asked to evaluate their effectiveness. From the ranked responses and qualitative feedback, a clear preference emerged in favour of traditional auditory metronomes, particularly the click-track, when it came to perceived timing precision.

Participant Number	**1**	**2**	**3**	**4**	**5**	**6**
Participant Skill Level	Professional	Professional	Beginner	Advanced	Advanced	Advanced
Metronome Method Ranking (1 to 6)						
1	Click Only	Click Only	Click Only	Click and Haptics	Click Only	Click and Haptics
2	Click and Haptics	Click and Haptics	Click and Haptics	Click Only	Click and Haptics	Click Only
3	Click and Light	Click and Light	Light and Haptics	Click and Light	Light and Haptics	Click and Light
4	Light and Haptics	Haptics Only	Click and Light	Light and Haptics	Click and Light	Light and Haptics
5	Light Only	Light and Haptics	Haptics Only	Haptics Only	Haptics Only	Haptics Only
6	Haptics Only	Light Only	Light Only	Light Only	Light Only	Light Only

Table 2 Metronome Preference Ranking for each drummer

In participant rankings, the click-track consistently appeared near the top for precision, often selected as the most effective method. Respondents cited its clear, consistent beat as aiding rhythmic focus, with one participant commenting that “it allowed me to lock in my timing better than the others.” Meanwhile, the haptic method was polarising, a few participants appreciated the tactile cue as an unobtrusive supplement, but others noted difficulty sensing precise rhythmic placement, especially during louder musical sections where physical feedback could be masked. The light pulse was most often ranked lowest in terms of precision, with criticisms pointing to the challenge of visually tracking the light while performing, and its limited effectiveness in conveying groove or feel. Notably, when participants used combined methods (e.g., haptic and light), responses suggested some benefit in terms of supplementary support, but not necessarily improved timing precision. Instead, these were more commonly associated with reduced auditory fatigue or enhanced comfort, not accuracy.

In contrast, auditory methods such as the click-track, while still rated highly for timing accuracy, were seen as problematic from a hearing health standpoint. Several participants noted that “adding another sound layer” contributed to listening fatigue or clashed with ensemble textures. The light pulse method, though theoretically non-auditory, did not perform as well in perceived sound reduction impact. This may be attributed to its practical shortcomings, difficulty in maintaining visual focus, limited peripheral awareness, and incompatibility with dynamic head or body movement during performance. Some participants suggested that hybrid systems, particularly combinations of haptic and visual cues, might offer the best balance between silent operation and effective feedback. While none of the combinations outperformed the haptic method alone in sound exposure rankings, they were still seen as promising, especially for drummers concerned with both timing and hearing health.

3.4.2 Confidence, Comfort, and Ease of Use Across Metronome Modalities

Questionnaire responses revealed notable differences in confidence, comfort, and ease of maintaining timing across metronome types. Auditory methods, particularly the click track, received the highest confidence and ease-of-use ratings. Participants described the click as clear and familiar, allowing them to relax and focus on feel, aligning with auditory-motor entrainment theories that emphasise rhythm processing efficiency (Repp and Su, 2013[34]).

Haptic feedback produced more varied results. While some participants felt “in control,” others reported reduced confidence due to weak or unclear vibrations. These findings reflect research suggesting that tactile cues must be distinct and context-sensitive to be effective (Brewster and Brown, 2004[35]). Despite this, haptic cues were rated as the most comfortable, with participants describing them as “less fatiguing” and “more immersive,” supporting claims that tactile systems reduce sensory strain (Cholewiak, 1999[36]). The visual pulse method received the lowest ratings for both comfort and usability. Participants reported difficulty maintaining focus and described the cue as distracting, consistent with evidence that visual processing is less efficient for temporal coordination (Posner and Petersen, 1990[37]; van der Wel et al., 2010[38]).

3.4.3 Sound Exposure Reduction: The Role of Non-Auditory Metronomes in Protecting Hearing Health

The haptic metronome method was overwhelmingly ranked as the most effective for this purpose. Participants consistently placed it at the top of their sound exposure reduction rankings, recognising that it entirely bypassed the auditory pathway. Comments such as “I could feel the pulse without any additional sound” and “ideal for loud environments” reflect an intuitive awareness of how tactile cues can preserve temporal accuracy without increasing acoustic load. This aligns with emerging research into vibrotactile feedback systems for musicians, which show promise for silent cueing in both live and studio contexts (Eggenberger et al., 2020[39]).

3.4.4 Thematic Analysis of Qualitative Responses

Open-ended feedback provided valuable insights into how drummers experienced each metronome method, highlighting key themes around familiarity, embodiment, visual processing, contextual use, and hearing health.

Familiarity vs. Novelty

Many participants reflected on the tension between the familiarity of auditory metronomes and the novelty of haptic or visual systems. Several noted that the haptic device “took getting used to” but eventually “felt natural,” whereas the light pulse was often described as “distracting.” These responses align with cognitive load theory, suggesting that unfamiliar tools initially demand greater mental effort before users adapt (Sweller, 1988[40]).

Embodiment and Physicality

The haptic method was frequently described in embodied terms, with participants reporting they could “feel the beat” and felt “more grounded” during performance. This reflects theories of sensorimotor integration, where bodily feedback supports rhythmic coordination (Leman, 2008[41]). However, some found the vibration inconsistent, highlighting the need for customisable feedback intensity or calibration.

Visual Overload and Disruption

The light-based cue received largely negative feedback. Participants reported that focusing on the light diverted attention from playing, describing it as “distracting” and “hard to follow.” This aligns with research showing that visual feedback can overload attention during real-time motor tasks (Kleiner et al., 2004[42]).

Contextual Suitability

Participants emphasised that no single method suits all contexts. Haptic feedback was preferred in loud live environments, while click-tracks were favoured for studio use. Some proposed alternating methods to reduce fatigue and maintain focus, supporting educational perspectives that metronomic tools should be adaptable to context and learning goals.

Accessibility and Hearing Health

A recurring theme was hearing protection and accessibility. Participants recognised non-auditory methods, especially haptics, as valuable for reducing sound exposure, with one describing it as “a breakthrough for saving ears." These insights reinforce the need for silent cueing systems that promote both performance quality and musician wellbeing.

4.5 Limitations

This study provides valuable insights into how different metronome types influence timing precision and sound exposure, though several limitations must be acknowledged. The small sample size limits generalisability, and the controlled studio environment may not reflect real-world variability in performance. Individual sensory differences likely influenced responses to visual and haptic cues, especially in the Light Only and Haptics Only conditions. While fixed sound pressure levels ensured consistency, they did not account for natural volume variation, and the focus on steady drumming reduced ecological validity. Additionally, risks of NIHL were inferred rather than clinically measured, and self-reporting bias may have influenced some responses. However, the use of a repeated-measures design and triangulation with objective timing and SPL data helped mitigate these effects.

5 QUESTIONNAIRE RESULTS AND ANALYSIS

5.1.1 Demographic Overview

An online survey was distributed via drumming communities and social media to gather responses from at least 50 participants. It collected demographic data, drumming experience, use of click tracks and IEMs, NIHL awareness, and experiences with alternative metronomes. Closed and open-ended questions were used to reduce ambiguity and bias (Rosenman, Tennekoon & Hill, 2011[43]).

A total of 63 drummers participated in this study, spanning a wide range of ages, drumming experience, and self-assessed hearing abilities. The sample was predominantly younger, with 41% aged 18–24 and 25% aged 35–44; only 5% were over 55, indicating that findings may best reflect contemporary drumming practices.

Most participants (58.7%) had been playing for 4–12 years, while 20.6% had over 12 years of experience. Beginners (<2 years) comprised 7.9% of the sample. On a self-rated hearing scale (1 = poor, 5 = perfect), the mean score was 3.38 (SD = 0.92), with 44.4% rating their hearing as "average" (3) and 12.7% rating it below average (1–2), highlighting early concerns about hearing health.

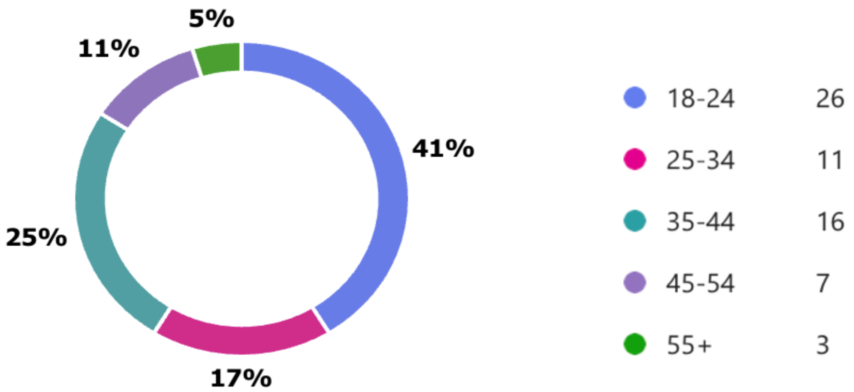

Figure 3 Pie Chart to show the Age Demographic of questionnaire respondents indicating over half the respondents being within the 18-34 age group

5.1.2 Metronome Usage Patterns

Metronome use differed significantly between practice and performance. While 49.2% of drummers used a metronome during practice, only 30.2% reported using one in live performance. A critical analysis of results revealed a significant association between experience level and metronome use during practice, with less experienced drummers (<8 years) more likely to use metronomes. Younger drummers (18–24) also showed higher usage rates in both settings compared to older cohorts, suggesting a generational shift toward digital practice tools.

5.2.3 Awareness and Preferences for Metronome Methods

Awareness of metronome types varied: auditory metronomes were nearly universally known (96.8%), while 68.3% were aware of visual metronomes and only 34.9% knew of haptic devices. However, active usage was much lower, 19% had tried visual metronomes and fewer than 10% had used haptic ones. Notably, 25.4% of participants expressed a strong preference for non-auditory methods. This group significantly overlapped with respondents who rated their hearing below 3, suggesting that concern for auditory health motivates openness to alternative timing technologies.

5.2.4 Perceived Impact on Performance

Most respondents (71.4%) believed metronomes improved timing and consistency during practice, a belief more common among drummers with less than 8 years of experience. However, more experienced drummers (≥12 years) often expressed scepticism. Thematic analysis of open responses revealed three primary perspectives:
Enhancement of Technical Precision: “It tightens up my fills and exposes weak spots.”
Inhibition of Musical Feel: “Sometimes it kills the groove.”
Auditory Fatigue: “The click in my ears gets exhausting after a while.”
Among those rating their hearing below 3, concerns about ear fatigue and tinnitus were common, further motivating interest in haptic alternatives.

5.2.5 Openness to Haptic and Visual Technologies

Overall, 57.1% expressed willingness to try non-auditory metronomes, with enthusiasm strongest among younger participants and those concerned about hearing loss. As one participant put it, “Feeling the beat might be better than hearing it, especially after long gigs.” Visual metronomes, though better known, were less favoured due to concerns about stage lighting, eye fatigue, and distraction during energetic performances. Haptic devices were viewed as promising for their discrete, body-based feedback.

5.2.6 Hearing Health Awareness and Behaviour

Although 82.5% of participants reported awareness of hearing risks, only 47.6% regularly used hearing protection. Younger drummers were more proactive in this regard. Thematic analysis revealed a common narrative of retrospective regret among older drummers: “I wish I had started protecting my ears earlier” and “Now I have constant ringing.”

Those relying heavily on in-ear click tracks were significantly more likely to report symptoms of temporary threshold shifts. Further to this, 34% of respondent drummers stated they had poor to moderate knowledge on hearing protection measures that are available to them. This is a substantial percentage suggesting a lack of education in the music industry regarding hearing health and NIHL preservation techniques. Additionally, only 4% of drummers chose their preferred metronome method based off hearing health benefits, exaggerating the reduced understanding of the effects of NIHL from click track usage among drummers.

5.2.8 Visual Summary

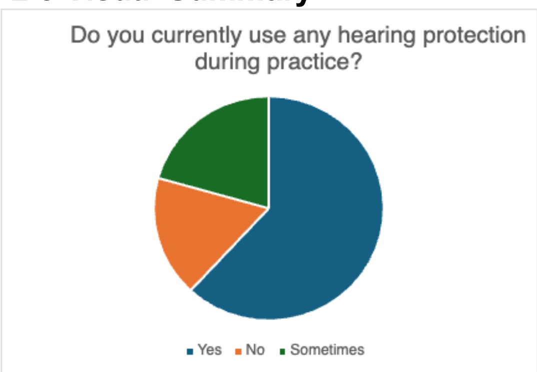

Figure 4 Chart to show over 50% of drummers use hearing protection during practice and rehearsals

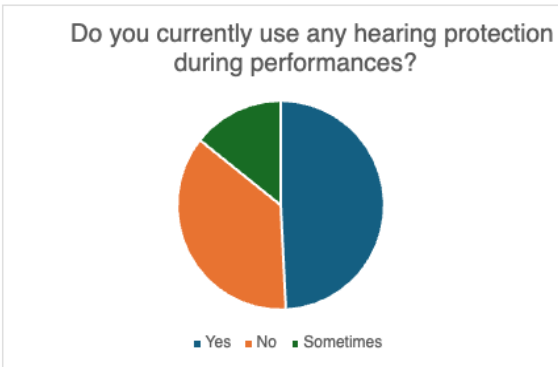

Figure 5 Chart to show over 50% of drummers do not wear always wear hearing protection in performance settings

A comparison of Figure 4 and Figure 5 show the percentage of drummers who use hearing protection during rehearsals compared to in live environment settings. With the percentage of drummers who claimed they do not use any hearing protection during performances increasing by 20% compared to during practice indicates a higher risk of NIHL in live music settings.

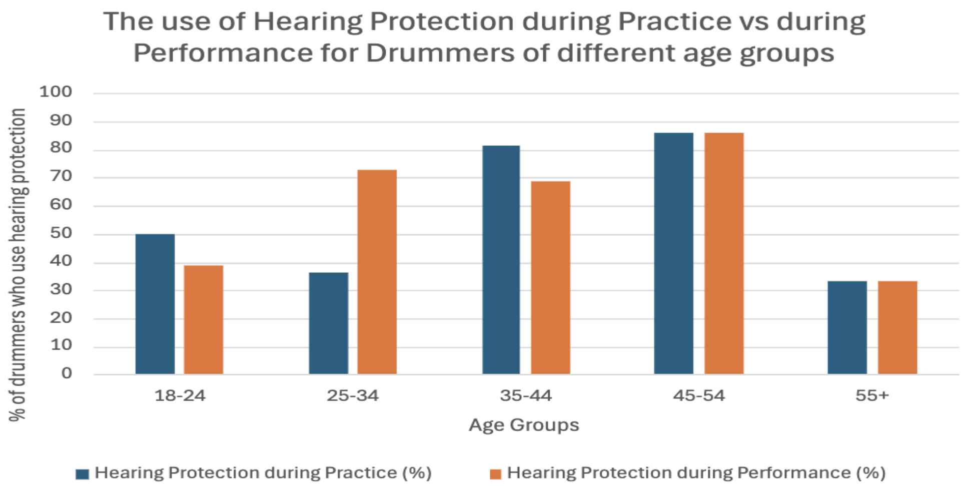

Figure 6 Bar Chart illustrating the generational changes in using hearing protection during Practice vs during Performance

Figure 6 illustrates age-related trends in hearing protection use among drummers during practice and live performance. In the 18–24 group, usage dropped from 52% in practice to 41% in performance, suggesting inconsistent habits or a focus on auditory clarity on stage. The 25–34 group showed the reverse pattern, prioritising protection in high-risk performance settings (69%) over practice (38%). The 35–44 and 45–54 groups demonstrated the highest and most consistent use, with over 80% during practice and up to 86% in performance, likely reflecting greater awareness and experience. In contrast, the 55+ group reported the lowest rates (33% in both contexts), possibly due to generational gaps in education, reduced exposure, or perceived limitations of protection. These patterns support previous findings that age, risk perception, and experience influence hearing conservation behaviours.

Summary Table of Key Quantitative Results:

Measure	Key Statistic	Note
Mean self-rated hearing	3.38 (SD = 0.92)	12.7% rated it as 1 or 2
Metronome use in practice	49.2%	Higher in younger, less experienced drummers
Metronome use in performance	30.2%	Considerably lower than in practice
Awareness of haptic metronomes	34.9%	Very low active usage
Regular hearing protection use	47.6%	Despite 82.5% awareness
Preference for non-auditory metronomes	25.4%	Especially among those with hearing concerns

Table 3 Summary of Key Quantitative Results from Questionnaire Analysis

A complete dataset and detailed analysis of the results are presented in the full report (Bickmore, T, 2025[44]).

6 CONCLUSIONS

This study examined how different metronome types influence drummers’ timing accuracy while reducing sound exposure and the risk of noise-induced hearing loss. Findings indicate that auditory click tracks provide the highest timing precision but carry greater auditory risk, whereas visual and haptic metronomes lower sound exposure but reduce accuracy when used independently. Combining a low-level click track with haptic or visual cues maintained strong timing precision while significantly reducing sound exposure, offering a practical balance between performance accuracy and hearing protection. These results highlight the potential of multisensory metronome systems to promote safer rehearsal and performance practices.

Based on the findings, further research is recommended to explore haptic metronome systems in greater depth across a range of instrumentalists. Investigations should focus on their effectiveness, user comfort, and optimal placement to adapt these systems to diverse musical contexts. The combination of haptic feedback with reduced sound level click tracks is especially promising and warrants deeper study, particularly in live and rehearsal environments. The study underscores the urgent need for more robust hearing health education, equipping musicians with a clearer understanding of the risks associated with high sound pressure levels and practical strategies to protect their hearing. Educational initiatives should clarify what constitutes dangerous exposure and offer guidance on monitoring and reducing personal sound levels during practice and performance. Additionally, the development of real-time sound exposure monitoring tools, such as wearable devices or mobile applications, is strongly encouraged. These tools could provide live feedback, empowering musicians to make informed decisions and develop long-term habits that safeguard their auditory health.

In conclusion, this research supports a multifaceted approach to hearing conservation, combining technological innovation, education, and practical monitoring. It should be considered a starting point to obtain a robust understanding on the integrated use of auditory, visual, and haptic metronomes, which present a promising path to maintain musical precision while significantly reducing auditory risk. Continued development and application of these strategies are essential to advancing safer musical practices in both professional and educational settings.

7 REFERENCES

1. Ding, T., Yan, A. and Liu, K. (2019). What is noise-induced hearing loss? *British Journal of Hospital Medicine*, 80(9), pp.525–529. doi:https://doi.org/10.12968/hmed.2019.80.9.525. (Accessed: 30/10/24).
2. Clark, W.W. (1991). Noise exposure from leisure activities: a review. *The Journal of the Acoustical Society of America*, [online] 90(1), pp.175–181. doi:https://doi.org/10.1121/1.401285. (Accessed: 21/10/25).
3. Konings, A., Laer, L.V. and Camp, G.V. (2009). Genetic Studies on Noise-Induced Hearing Loss: A Review. *Ear and Hearing*, 30(2), pp.151–159. doi:https://doi.org/10.1097/aud.0b013e3181987080. (Accessed: 30/10/24).
4. Early, S., Du, E., Boussaty, E. and Friedman, R. (2022). Genetics of noise-induced hearing loss in the mouse model. *Hearing Research*, p.108505. doi:https://doi.org/10.1016/j.heares.2022.108505. (Accessed: 30/10/24).
5. Ciorba, A., Bianchini, C., Pelucchi, S., & Pastore, A. (2012) 'Noise-induced hearing loss and tinnitus in musicians: A systematic review', *Noise and Health*, 14(58), pp. 130-137. doi: 10.4103/1463-1741.97376.
6. Sliwinska-Kowalska, M., & Zaborowski, K. (2017) 'Occupational noise-induced hearing loss among musicians: A review', *International Journal of Occupational Medicine and Environmental Health*, 30(4), pp. 527-536. doi: 10.13075/ijomeh.1896.01179.
7. Barker, D., Kelly, L., & Jones, G. (2017) 'The impact of hearing protection devices on hearing fatigue and auditory performance in musicians', *Journal of Audiology and Speech Pathology*, 45(2), pp. 98-107. doi: 10.1016/j.jaudsp.2017.01.004.
8. Ziegler, J., Schwartze, M., & Pires, S. (2018) 'Musicians' hearing protection practices: A survey of usage and attitudes towards hearing protection', *Hearing Research*, 365, pp. 17-25. doi: 10.1016/j.heares.2018.02.001.

9. Münster, L., Meyer, B., & Franck, M. (2020) 'Protecting musicians' hearing: A review of hearing protection strategies', *Noise Control Engineering Journal*, 68(3), pp. 196-205. doi: 10.3397/2469-4144.2020.003.
10. Sowiński, J. and Dalla Bella, S. (2013) ‘Synchronization to auditory and visual rhythms in musicians and non-musicians’, *Acta Psychologica*, 144(3), pp. 566–572.
11. Einarson, K.M. and Trainor, L.J. (2016) ‘Multisensory interaction in timing: Auditory dominance in metronome perception’, *Frontiers in Psychology*, 7, p. 1243. Available at: https://www.frontiersin.org/articles/10.3389/fpsyg.2016.01243/full (Accessed: 30/01/25).
12. Paydarfar, D., Patel, A.D. and Iversen, J.R. (2017) ‘A preliminary study: Is the metronome harmful or helpful?’, *Journal of Music Education Research*, 19(3), pp. 267–279. Available at: https://files.eric.ed.gov/fulltext/EJ1146312.pdf (Accessed: 30 January 2025).
13. Hove, M.J., Fairhurst, M.T. and Keller, P.E. (2024) ‘Inner sense of rhythm: Percussionist brain activity during rhythmic processing’, *Frontiers in Neuroscience*, 18, p. 1342326. Available at: https://www.frontiersin.org/articles/10.3389/fnins.2024.1342326/full (Accessed: 30/01/25).
14. Hellmer, K. and Madison, G. (2017) ‘Correlated microtiming deviations in jazz and rock music’, *Journal of New Music Research*, 46(1), pp. 1–10. Available at: https://arxiv.org/abs/1710.05608 (Accessed: 30/01/25).
15. Berg, Jan; Johannesson, Tomas; Löfdahl, Magnus; Nykänen, Arne. (2017). *E-library page - AES*. [online] Available at: https://aes2.org/publications/elibrary-page/?id=18673 (Accessed: 30/10/24).
16. Remache-Vinueza, B., Trujillo-León, A., Zapata, M., Sarmiento-Ortiz, F. and Vidal-Verdú, F. (2021). Audio-Tactile Rendering: A Review on Technology and Methods to Convey Musical Information through the Sense of Touch. *Sensors*, [online] 21(19), p.6575. doi:https://doi.org/10.3390/s21196575.
17. DeGuglielmo, N., Lobo, C., Moriarty, E.J., Ma, G. and Dow, D.E. (2021). Haptic Vibrations for Hearing Impaired to Experience Aspects of Live Music. *Springer eBooks*, pp.71–86. doi:https://doi.org/10.1007/978-3-030-92163-7_7. (Accessed: 15/01/2025).
18. Young, D., Murphy, J., & Weeter, J. (2017) ‘Haptic Feedback in Digital Musical Instruments: Evaluating Functionality and Usability’, in *New Interfaces for Musical Expression (NIME)*. doi: 10.1007/978-3-319-58316-7_6
19. Yoshida, T., Nakamura, H., & Tanaka, M. (2023) ‘Effects of Multimodal Stimuli on Human Response Times Using Mobile Devices’, *arXiv preprint*. Available at: https://arxiv.org/abs/2305.17180 (Accessed: 19/03/25).
20. Flores Ramones, A. and del-Rio-Guerra, M.S. (2023). Recent Developments in Haptic Devices Designed for Hearing-Impaired People: A Literature Review. *Sensors*, 23(6), p.2968. doi:https://doi.org/10.3390/s23062968.
21. Bishop, L., Cancino-Chacón, C. and Goebl, W. (2019). Moving to Communicate, Moving to Interact. *Music Perception*, 37(1), pp.1–25. doi:https://doi.org/10.1525/mp.2019.37.1.1.
22. Colley, I.D., Varlet, M., MacRitchie, J. and Keller, P.E. (2018). The influence of visual cues on temporal anticipation and movement synchronization with musical sequences. *Acta Psychologica*, 191, pp.190–200. doi:https://doi.org/10.1016/j.actpsy.2018.09.014.
23. Su, K., Liu, X. and Shlizerman, E. (2020). *Audeo: Audio Generation for a Silent Performance Video*. [online] arXiv.org. Available at: https://arxiv.org/abs/2006.14348 (Accessed: 05/02/25).
24. Chebat, J-C., Gelinas-Chebat, C. and Filiatrault, P. (1993). Interactive Effects of Musical and Visual Cues on Time Perception: An Application to Waiting Lines in Banks. *Perceptual and Motor Skills*, 77(3), pp995-1020. doi:https://doi.org/10.2466/pms.1993.77.3.995.
25. Teichner, W. H. (1954) ‘Recent studies of simple reaction time’, *Psychological Bulletin*, 51(2), pp. 128-149. doi: 10.1037/h0055372
26. Young, D., Murphy, J., & Weeter, J. (2020) ‘A Qualitative Analysis of Haptic Feedback in Music-Focused Exercises’, *ResearchGate*. Available at: https://www.researchgate.net/publication/344828316_A_Qualitative_Analysis_of_Haptic_Feedback_in_Music_Focused_Exercises (Accessed: 19/03/25).
27. Lee, J., Kim, S., & Choi, H. (2023) ‘Enhancing Virtual Reality Concerts with Haptic Feedback: A Qualitative and Empirical Analysis’, *Arts*, 12(4), p. 148. doi: 10.3390/arts12040148
28. Ernst, M. O. & Banks, M. S. (2002) 'Humans integrate visual and haptic information in a statistically optimal fashion', *Nature*, 415(6870), pp. 429-433. doi:10.1038/415429a.

29. López-Moliner, J. & Soto-Faraco, S. (2007) 'Vision affects tactile processing in a temporal discrimination task', *Cognitive Brain Research*, 25(3), pp. 812-817. doi:10.1016/j.cogbrainres.2007.01.009.
30. Harrar, V. & Harris, L. R. (2005) 'Simultaneity sensitivity for tactile and visual stimuli', *Brain Research*, 1073(1), pp. 316-322. doi:10.1016/j.brainres.2005.12.072.
31. Sarrazin, J. C., Giraudo, M. D., Pailhous, J., & Bootsma, R. J. (2004) 'Dynamics of balancing space and time in memory: The kappa effect', *Journal of Experimental Psychology: Human Perception and Performance*, 30(3), pp. 411-430. doi:10.1037/0096-1523.30.3.411.
32. Kanai, R., Paffen, C. L. E., Hogendoorn, H. & Verstraten, F. A. J. (2011) 'Time dilation in dynamic visual displays', *Journal of Vision*, 11(8), pp. 1-10. doi:10.1167/11.8.1.
33. Braun, V. and Clarke, V., (2006). *Using thematic analysis in psychology*. Qualitative Research in Psychology, 3(2), pp.77–101. doi:10.1191/1478088706qp063oa.
34. Repp, B.H. and Su, Y.H., (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, 20(3), pp.403–452.
35. Brewster, S. and Brown, L.M., 2004. Tactons: Structured tactile messages for non-visual information display. *Proceedings of the Fifth Conference on Australasian User Interface*, 28, pp.15–23.
36. Cholewiak, R.W., (1999). The perception of tactile distance: Influences of body site, space, and time. *Perception*, 28(7), pp.851–875.
37. Posner, M.I. and Petersen, S.E., (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13(1), pp.25–42.
38. van der Wel, R.P.R.D., Sebanz, N. and Knoblich, G., (2010). Multisensory cues improve sensorimotor synchronization. *European Journal of Neuroscience*, 31(10), pp.1828–1835.
39. Eggenberger, F., Molnar, M., Linn, J. and Grosshauser, T., 2020. *A vibrotactile metronome for musicians: Design, evaluation, and comparison with auditory cues*. Journal of New Music Research, 49(2), pp.123–137.
40. Sweller, J., (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12(2), pp.257–285. Available at: https://www.sciencedirect.com/science/article/pii/0364021388900237 .ScienceDirect+1ScienceDirect+1 (Accessed: 02/01/25)
41. Leman, M., (2008). *Embodied music cognition and mediation technology*. Cambridge, MA: MIT Press. Available at: https://mitpress.mit.edu/9780262122931/embodied-music-cognition-and-mediation-technology/ .Open Library+2MIT Press+2mitpressbookstore+2
42. Kleiner, M., Brainard, D. and Pelli, D., (2007). What's new in Psychtoolbox-3? *Perception*, 36(Supplement), pp.1–16. Available at: https://nyuscholars.nyu.edu/en/publications/whats-new-in-psychtoolbox-3 .
43. Rosenman, R., Tennekoon, V. and Hill, L.G. (2011). Measuring bias in self-reported data. International Journal of Behavioural and Healthcare Research, [online] 2(4), pp320-332. doi:https://doi.org/10.1504/ijbhr.2011.043414. (Accessed: 20/11/24).
44. Bickmore, T., (2025) 'Precision vs. Protection: A Comparative Study of Metronome Devices on Temporal Accuracy and Sound Exposure Risks for Drummers in Live Music'. Undergraduate dissertation, University of Derby.