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ORIGINAL PAPER

Hearing loss prevention at loud music events via real-time visuo-haptic feedback

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Abstract

Hearing loss is becoming a global problem, partly as a consequence of exposure to loud music. People may be unaware about the harmful sound levels and consequent damages caused by loud music at venues such as discotheques or festivals. Earplugs are effective in reducing the risk of noise-induced hearing loss but have been shown to be an insufficient prevention strategy. Thus, when it is not possible to lower the volume of the sound source, a viable solution to the problem is to relocate to quieter locations from time to time. In this context, this study introduces a bracelet device with the goal of warning users when the music sound level is too loud in their specific location, via haptic, visual or visuo-haptic feedback. The bracelet embeds a microphone, a microcontroller, an LED strip and four vibration motors. We performed a user study where thirteen participants were asked to react to the three kinds of feedback during a simulated disco club event where the volume of music pieces varied to reach a loud intensity. Results showed that participants never missed the above threshold notification via all types of feedback, but visual feedback led to the slowest reaction times and was deemed the least effective. In line with the findings reported in the hearing loss prevention literature, the perceived usefulness of the proposed device was highly dependent on participants' subjective approach to the topic of hearing risks at loud music events as well as their willingness to take action regarding its prevention. Ultimately, our study shows how technology, no matter how effective, may not be able to cope with these kinds of cultural issues concerning hearing loss prevention. Educational strategies may represent a more effective solution to the real problem of changing people's attitudes and motivations to want to protect their hearing.

Keywords Hearing loss prevention · Multisensory feedback · Loud music · Wearables

1 Introduction

According to different studies, hearing loss is becoming a global problem [1–3]. In 2021, the World Health Organization has estimated that by 2050 about 2.5 billion people will have some degree of hearing loss [4]. Hearing loss can have multiple causes, but nowadays unsafe music listening practices certainly represent a considerable part of the problem [5–7]. Premature hearing decline is worryingly common among young adults. To date, up to 1.3 billion teenagers and young adults (12 – 34 years) are exposed to loud entertainment venues where they are at potential risk of noise-induced hearing loss [8]. In response to the issue of the potential damage of exposure to loud music especially by the young population, recently, the Dutch Health Council has advised the government to lower the maximum sound level allowed at festivals and parties [9].

Noise-induced hearing loss refers to a gradual and cumulative decline in auditory function that follows repeated exposure to loud noise. It is known that a temporary threshold shift occurs after loud sound exposure [10] and it is widely accepted that repeated temporary threshold shifts can lead to accumulated cellular damage which can cause permanent threshold shifts [11, 12]. According to the World Health Organization [13] listening to music can be made safer in three ways: (1) decreasing the sound level, (2) decreasing the exposure time to sound, (3) reducing the frequency of exposure. Thus, to allow young adults to continue their exposure to sounds as much as possible while prevent hearing loss, the viable solutions are to decrease the sound level as well as limit the time and frequency of exposure to loud sounds. Recently, the World Health Organization decreased the recommended maximum average sound level for venues to 100 decibels

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(dB) [14]. Nevertheless, according to the regulations of the National Institute for Occupational Safety and Health of the United States, 100 dB is still too loud in terms of potential risk of noise-induced hearing loss.

Typically, people attending music festivals or dancing in big clubs are not aware of the current level of dB [10, 15]. In order to help prevent hearing loss, people attending loud music events should be warned and made aware of the areas in the music venue which pose the greatest risk of hearing damage, and should be guided towards the safe ones. This could especially be useful at festivals or in big clubs, as these locations have sound level differences within the venue. Wearable technologies equipped with real-time sensing and multisensory feedback could be exploited to inform the user about the potential risks of damage for the hearing system. However, differently from other fields such as sport [16], to date, relatively scarce research has been conducted to address such a topic via multisensory techniques and human-computer interaction methods.

To address the issue of hearing loss prevention via technological means, in this paper we propose "BrrraceLED", a bracelet device encompassing a microphone as well as LED and actuators that provide real-time visuo-haptic notification to users when the sound level is above a given threshold. The device was conceived to be given to people attending festivals or clubs, as bracelets are widely used in these contexts. The use of visual and haptic feedback was devised to provide information through the free sensory channels of vision and touch.

We performed a user study to assess its effectiveness and users' perceptions in terms of usefulness, liking, practicality, acceptability. We experimentally tested the device in controlled conditions where participants attended a simulated disco club event. Our aim was to assess which kind of sensory feedback, whether visual, haptic or visuo-haptic, was more effective in steering people away from harmful audio levels. Moreover, we were interested in assessing how users judged the practical utilization of the device while attending music events.

2 Related work

2.1 Hearing risks awareness

Noise reduction programmes aimed at leisure activities, such as music listening through personal music players or through amplifiers, face the difficulty that the noise source is often the same one that is viewed as pleasurable by participants. In addition, loud music related activities often exist within a social setting, with additional peer influences that may influence behavior [7, 17]. Different studies have investigated the extent to which people are aware of the risks related to hearing issues during exposure to loud music and whether they are willing to take countermeasures or not. The authors of [18] reported how over time regular clubbers become conditioned to enjoy loud sound in itself, proposing the that the exposure to loud sound also causes adaptation within the auditory system, and as a consequence that there is both a desire for, and tolerance of, loud sound during leisure time.

The use of personal music players and similar products are commonly associated with the development of hearing loss [19–21]. Notably, the study reported in [22] about the relation of these devices and hearing loss concluded that "most adolescents would not accept any interference with their music-exposure habits". This suggests that most of young people are not willing to accept an intervention to help prevent noise-induced hearing loss. Yet, we believe that this result should not discourage researchers to investigate technological means to raise awareness about situations of risk, an investigation that is especially relevant and useful to those who instead are willing to protect themselves.

Other studies have investigated the hearing-related behaviours and perceptions of individuals exposed to loud music at festivals, discotheques and other similar venues. The study reported in [23] found that around 40% of young people consider the music at discotheques, pop and rock concerts, and techno parties too loud, whereas the 3% of involved participants considered sound levels at these events to be too low. The authors concluded that young people neither demand nor require the excessive sound levels typical of most music events. In [17], the authors found that in a sample of four hundred and eighty-four young people, approximately one in five participants reported using listening volumes at levels perceived to be dangerous. The study reported in [24] compared the adolescents' attitudes toward loud music in relation to a set of self-perceived auditory symptoms and psychological variables such as norms, preparedness to take risks and risk-judgment in noisy situations. The authors concluded that psychological variables such as norms, preparedness to take risks and risk-judgment were found to be more strongly associated with attitudes toward loud music and should therefore be considered to a greater extent in preventive work.

In a different vein, the study reported in [25] investigated the perceptions of music students in relation to exposure to loud music and consequent health risks. The results showed that music students are exposed to high sound levels in the course of their academic activity. Nevertheless, students were not entirely aware of the health risks related to exposure to high sound pressure levels. The authors concluded that their findings highlight the importance of starting intervention in relation to noise risk reduction at an early stage, when musicians are commencing their activity as students.

2.2 Hearing loss prevention

The study reported in [26] concluded that hearing loss is the fourth leading contributor to years lived with a disability worldwide and that the prevalence of hearing loss is greatest in low-income and middle-income nations. Prevention strategies to cope with such an issue are fundamental not only to ensure healthy conditions, but also to reduce the related negative impacts associated to social and economic costs.

Next to turning down the volume, the most known and widespread way of protecting our ears from hearing loss is the utilization of earplugs. These have been proven to be effective in preventing temporary hearing loss after loud music exposure [10, 27]. Nevertheless, a recent recommendation by the World Health Organization states that if a person was to use earplugs that provided 12 dB of attenuation within a venue with sound level limited to 100 dB, then such a person would be able to visit the venue at a greater frequency or stay longer, totaling up to around 6 h a week on average [13]. Therefore, earplugs surely represent a helpful strategy for the prevention of hearing loss, but not an optimal one. This calls for other technological and technological means to facilitate hearing loss prevention.

2.3 Sensory substitution technologies

In the past two decades a considerable amount of research has been conducted on different kinds of assistive technologies for the hearing-impaired population, which fall in the remits of the sensory substitution field [28]. Sensory substitution refers to substituting environmental information, which would normally be processed by a human sensory system but that is affected by some form of impairment, and translate this information into stimuli for some other sensory system that instead are working. Assistive technologies based on sensory substitution schemes include systems conceived for allowing deaf or hard of hearing users to appreciate music via visualizations [29, 30] or haptic stimuli [31, 32]. Examples of these technologies include haptic wearables that transform music into vibrotactile stimulations using different kinds of audio-to-touch mapping strategies [33–35].

However, thus far, to the authors' best knowledge, little attention has been devoted by researchers to the creation of multisensory technologies able to support the prevention of hearing loss in populations with normal hearing. In particular, to our best knowledge no study has investigated the use of visual or haptic feedback as a means to address the issue of notifying in real-time a user without hearing impairments about dangerous sound levels during loud music events. Multisensory technologies based on the senses of vision and touch may be a helpful means to provide real-time information about harmful sound levels conditions when users are unaware of the risks. Indeed, these sensory channels would be not occupied (or at least not entirely) as opposed to the auditory channel, and therefore they would be ready to receive information useful to users. In particular, wearable devices, such as bracelets, would be practical to use in contexts such as disco dancing or music listening at festivals.

2.4 Augmented bracelets

In the past two decades there has been a considerable interest in developing multisensory wearable devices to support human activities in a variety of contexts [16] (such as smartwatches [36, 37]). Among these, bracelets augmented with sensors and actuators have been proposed by several researchers in academia and industry. Noticeable examples include bracelets embedding vibrotactile motors that support the learning of musical rhythms [38], the guidance of blind skiers [39], the rehabilitation of stroke survivors [40]; devices encompassing actuators that can move the bracelet along the forearm to provide notifications about a given information [41]; bracelets augmented with LEDs and vibrotactile motors to facilitate human-human physical touch for individuals with autism spectrum disorder [42].

We contend that multisensory bracelets or other wearable devices have not been sufficiently investigated as a means for hearing loss prevention at loud music events or for other settings at risk of loud noise. Notably, there are commercially available solutions that go in such a direction. For instance, the Noise App for Apple's smartwatches detects loud sounds in the user's environment and notifies him/her when it thinks the user may be at risk for hearing damage. When one opens the Noise app, s/he can see a real-time measurement of the sound around himself/herself in dB, along with a short message letting the user know if the sound levels are "OK" or "Loud". These notifications occur only at the visual level. The prototype proposed in this study is different from existing solutions because these do not provide haptic feedback, but only visual feedback in terms of notifications and statistics. In particular, our design is different, because it exploits blinking at visual level and pulses at vibrotactile level, and more importantly aims at providing alerts in real-time. Furthermore, the effectiveness of such apps has not yet been scientifically evaluated. In our study we were interested in measuring the participants' reaction times in response to stimuli in the visual, haptic and visuo-haptic modalities. Therefore, we needed a technical solution that allowed us to perform such measurements. Moreover, if a designer wants to propose a new app for the Apple's smartwatch s/he is forced to use the hardware (e.g., a given number and type of actuators in a specific position) and software (e.g., the software development kit) provided by Apple. Our aim was to investigate a novel solution at hardware and software level without being bound by the hardware and software constraints of Apple or other manufacturers.

3 BrrraceLED

3.1 Assumptions

Our aim was that of providing a viable technological solution to reduce hearing loss risks at events with loud music. In the design process of BrrraceLED we made two main assumptions. The first was that users do not want to suffer from hearing loss and, therefore, that users are willing to protect their ears whenever possible. As hearing loss problems are more and more frequently appearing in the news, the awareness about this problem is becoming greater. Therefore, it is reasonable to assume that people get more eager to protect their own ears.

The second assumption was that festivals organizers will keep using wristbands for entrance control. As festivals have been successfully using this system for several years now, it is reasonable to assume that they will keep using wristbands. Moreover, discotheques often use bracelets, so also in that setting a bracelet-based device would not be perceived as being inappropriate or out of context.

3.2 Design

BrrraceLED was designed to provide three kinds of sensory feedback[1]:

1. *Haptic:* intermittent pulses lasting 500 ms and separated by 500 ms, delivered by multiple tiny vibrotactile motors to be embedded in the bracelet;
2. *Visual:* intermittent red flashes as above delivered via an LED strip placed on the surface of the bracelet;
3. *Visuo-haptic:* the synchronous combination of LEDs and motors.

These unimodal and bimodal stimulations would occur as soon as a software taking input from a small micro-phone embedded in the bracelet detects that the sound level is above a given amount of dB considered harmful (i.e., 100 dB [14]). Visual and haptic modalities were utilized to provide this information as the auditory sense can not be used for this purpose (as it is already used to process the music signals). In designing the sensory stimuli, we were aware that visual feedback could be less noticed in contexts where there are already concurrent colored flashing lights such as in the discotheques. Nevertheless, we hypothesized that it could have been a successful complement to haptic feedback as in presence of loud music vibrations due to low frequencies can be perceived by the whole body, thus masking the notifications provided by the bracelet via the sense of touch. Moreover, the sense of touch was considered as a sensory channel where to convey information in presence of a busy visual modality, e.g., when the user is watching a band during a concert. On the other hand, vision was considered as a sensory modality for feedback alternative to the sense of touch, considering that the latter could also be occupied in processing haptic inputs received by friends or other people dancing or moving near the user.

The device was conceived to be given at the entrance of a festival, for the double purpose of access control and hearing loss risk warning. As soon as the bracelets detects a sound level above threshold for a given amount of time considered dangerous the unisensory or multisensory feedback is generated (depending on how the device is configured). The feedback would continue until the user, having acknowledged the feedback, moves to a different, more protected location, i.e., the feedback would automatically stop as soon as the sound level becomes below the threshold. However, the user is empowered to turn off or acknowledge the alert thanks to a dedicated button. In this way, the bracelet can be useful for notifying people of the dangerous sound levels, but it is then up to the wearer to decide how to use this information (e.g., move to a quieter place or insert earplugs).

The battery should last sufficiently long to cover the whole duration of the festival. At the end of the festival experience, the user can return the bracelet to the organizers that will recharge it for the next festival.

3.3 Implementation

BrrraceLED is composed by the following components (see Fig. 1): a sport wristband; a Teensy 3.6 microcontroller; an electret condenser microphone; an audio shield to interface the microphone with the microcontroller; 4 vibrotactile coin motors embedded in the wristband; a neopixel strip with 8 red LEDs embedded in the wristband, placed all around the wrist on the part of the bracelet closer to the forearm; a push button placed on the bottom side of the wrist. The bracelet can be powered by a lipo battery, and can be easily complemented with a bluetooth/wi-fi module. Nevertheless, for the purpose of the evaluation experiment a USB cable was used: this was due to the fact that our aim was to record the participants' reaction times to the stimuli as detailed in Sect. 4. The bracelet could be easily enhanced with an RFID for entrance control at festivals.

The software of the microcontroller was implemented in C, leveraging the Teensy audio library. Specifically, the threshold to trigger the sensory feedback was set to 90 db(A), measured via a root mean square algorithm over a timespan of 2 s, following the calibration with an external sound level meter. Notably, such a 2 s duration selected to monitor whether a sound level exceeded the set thresh-

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[1] The name BrrraceLED was devised to represent the vibrations provided by the device (rrr as an onomatopoeia), to reflect the presence of the LED strip, and to indicate that the device is based on a bracelet.

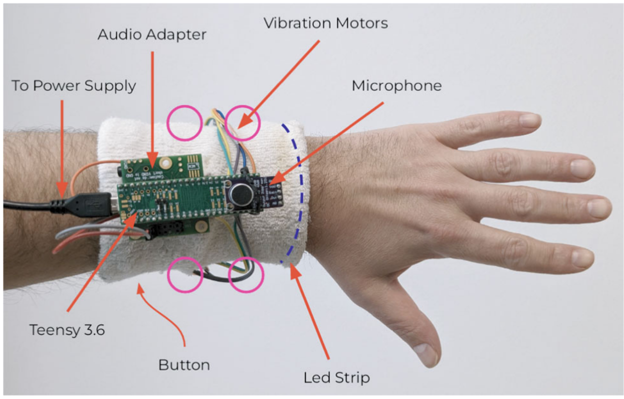

Fig. 1 A picture of the BrrraceLED prototype with the indication of its components

old in such timespan, was chosen only for the purposes of the experiment described in Sect. 4. For the use in real-world situations such a duration can be extended accounting for the fact that loud sounds become dangerous for a prolonged amount time rather than just a couple of seconds.

4 Evaluation

The goal of the experiment was twofold. First, to check whether the different kinds of sensory feedback could be noticed by participants and how long participants took to react to it. Second, to assess whether and to which extent the BrrraceLED was appreciated by participants while actually dancing and enjoying music. For this purpose we created a questionnaire based on the Technology Acceptance Model [43], which assesses the perceived usefulness and perceived ease of use. Before conducting the experiment, a pilot study was performed with four participants to test the device, the setting, and the experimental design.

4.1 Participants

Thirteen participants (6 females, 7 males), aged between 21 and 28 (mean = 24.5, standard deviation = 1.9) were recruited among the students of the University of Trento. Participants were selected according to four strict criteria: the participant should like to dance in disco clubs, should regularly go to discotheques (at least one per month), should have attended at least one music festival, and should have no hearing impairment.

Participants took 40 min on average to complete the experiment. The procedure, approved by the local ethics committee, was in accordance with the ethical standards of the 1964 Declaration of Helsinki.

4.2 Stimuli

The experiment consisted of 9 sessions. During each experimental session participants were provided with one dance music piece. Pieces were provided one after the other with no interruption (like during a DJ session in a disco club). These music pieces evolved in time with a variable amount of volume, thanks to an ad-hoc application built in the Pure Data multimedia programming environment, which run on a laptop. Specifically, at a randomized time during the music playback a linear increase in the average sound level (computed over 2 s) was accomplished from 70 dB(A) to 90 dB(A) across 10, 15 or 20 s. These conditions were due to ensure that participants were incapable of predicting when the sensory feedback was going to be provided by the bracelet. For each of these three conditions a haptic, visual or visuo-haptic feedback was repeated three times, in randomized order, for a total of 9 stimuli.

4.3 Procedure

The experiments took part in a room of a university students' residency in the city of Trento, which was configured to recreate the typical setting of a disco club, namely with a loudspeaker, colored lights flashing in the dark, and some glasses and bottles on a desk in a corner. The loudspeaker was placed at 2 ms from the dancing area. Figure 2 shows a schematic diagram of the experimental setup.

Firstly, participants were debriefed about the experimental procedure and were provided with an information sheet and consent form. Secondly, each participant was asked to wear a hat as well as earplugs. The former was to recreate the condition of a festival where sometimes organizers give the audience some gadgets such as hats with logo and name of the festival; the latter was due to two reasons. The first to avoid any possible harm or annoyance due to the sound level. The second to mask the actual sound level so participants could not be fully aware of it, and therefore the bracelet could be assessed for its effectiveness in conveying an auditory information via other sensory channels.

There was not a phase of familiarization with the system, as one research question was whether participants would have noticed the feedback. Yet before starting the actual experiment a warm up phase occurred where participants could enjoy dancing and the recreated discotheque atmosphere without having to perform any task. During each experimental session participants were asked to dance and to press the button on the bracelet if and as soon they noticed any change in it. A timer was created in the Pure Data software to record the participants' reaction time, measured as the time between when a sensory feedback was provided and when the participant pressed the button. Once the button was

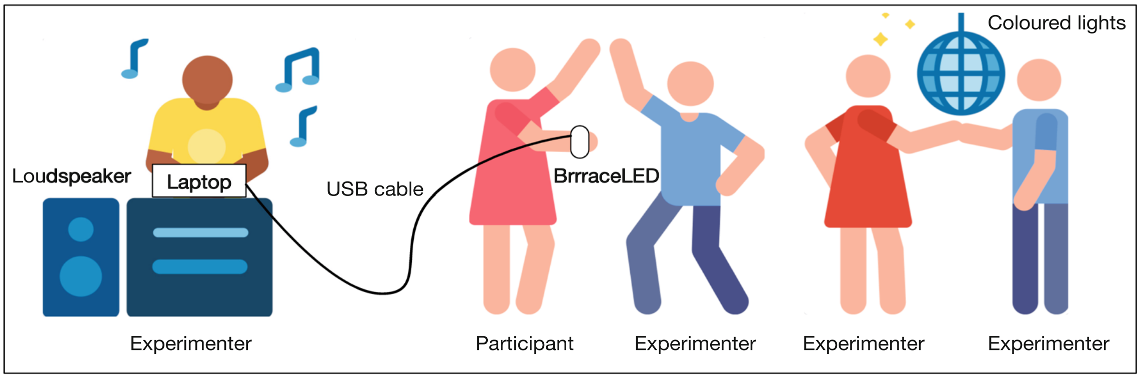

Fig. 2 A schematic diagram of the experimental setup

pressed, the music was turned back to the original volume of 70 dB(A).

Only one participant was involved during each experiment, but s/he was not dancing alone: four of the authors also joined the participant, three by dancing in the same area and one by acting as a DJ using the laptop that delivered the sound stimuli, so to recreate a more ecologically-valid condition.

At the end of the experiment participants were administered a questionnaire, which was composed of the following parts. First, participants were asked which sensory feedback they preferred during the experiment as well as which one they would like to receive the most during a real world scenario (e.g, a music festival). For both questions they were asked to motivate their choice.

Second, they were asked to assess for each type of feedback the following items on a 5-point Likert scale:

- *Experience.* I experienced the feedback as positive/negative [Strongly Negative; Strongly Positive]
- *Clarity.* The feedback was clear and noticeable [Strongly disagree; Strongly agree]
- *Effectiveness.* I would avoid places with loud music if the bracelet would provide feedback to me about it [Strongly disagree; Strongly agree]

Third, they were asked the following open-ended questions:

- Do you see yourself wearing a protecting bracelet at a festival? Please, explain your answer
- Do you use any kind of hearing protection in loud places (for example on a festival or in a club)? If yes, what kind of protection do you use?

Finally, participants were given the possibility to leave an open comment.

5 Results

5.1 Reaction time

No participant missed the sensory notification in any of the experimental sessions. A Kruskal-Wallis test was conducted to examine the differences in the reaction time between the three sensory feedback conditions. A significant main effect was found ($\chi^2(2)$, $p < 0.001$). A Wilcoxon post-hoc test with Bonferroni correction showed that the reaction time in visual feedback condition was significantly higher than that of the haptic and visuo-haptic conditions (respectively $p < 0.05$ and $p < 0.001$), as illustrated in Fig. 3a.

5.2 Questionnaire

Concerning the question about the type of sensory feedback preference during the experiment, 11 out of 13 participants preferred the haptic feedback condition (whereas only one preferred the visual only and one the visual-haptic ones). A significant one-tail binomial test showed that this amount is different from the null hypothesized value of probability of the chance level, i.e., 0.333 ($p < 0.001$, 95% confidence interval: [0.58, 1.0]). Similarly, for the visual and visuo-haptic conditions the binomial test turned to be significant (both $p < 0.001$) considering the probability of being below chance level (see Fig. 3b).

The reasons for preferring the haptic feedback were mostly attributed to the fact that it allows a notification without forcing the user to pay attention to the bracelet (e.g., *"I prefer haptic feedback because you can always feel the vibrations whereas you become aware of the visual feedback only when you look at the bracelet"*). Moreover, haptic feedback was deemed to be easier to perceive (e.g., *"I prefer vibration feedback since it was easier to detect and experience"*). In contrast, visual feedback was perceived as less useful because it could be confounded with the discotheques colored lights (e.g., *"I realized about the volume via*

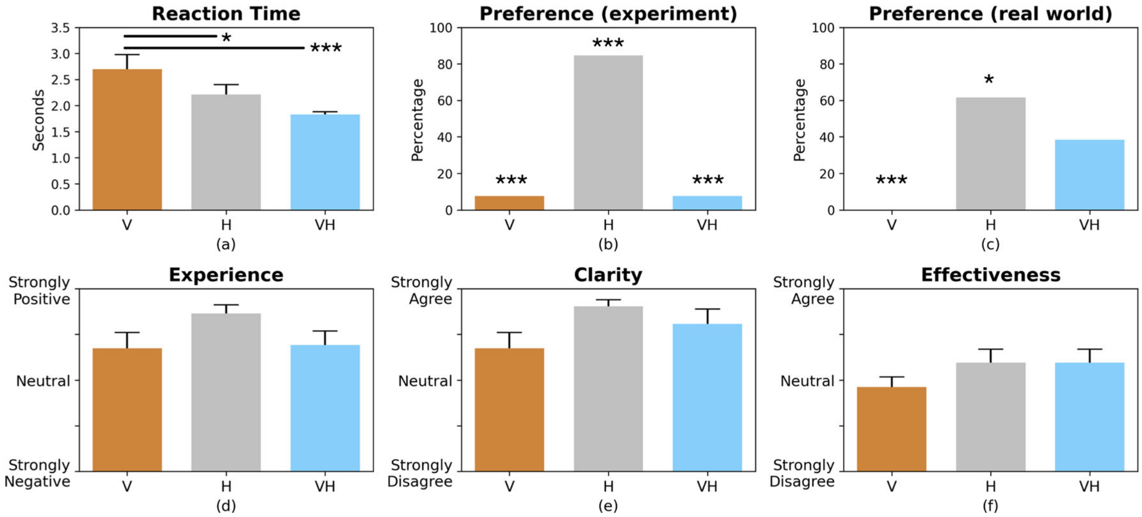

Fig. 3 Results of the experiment: **a** mean and standard error of the reaction times; **b** and **c** percentages for the preferences questions; **d**–**f** mean and standard error of the questionnaire items Experience, Clarity and Effectiveness. Legend: V = visual, H = haptic, VH = visuo-haptic; * = $p < 0.05$, *** = $p < 0.001$

the haptic feedback better, with the LED lights I can confuse myself with the club lights"), or because it was requiring to have a constant look at the device (e.g., *"The haptic feedback doesn't depend on my eyes being open or seeing my wrist, which can be hard in a crowd and in a chaotic place. It's also quite discreet, doesn't disturb much"*). Furthermore, the visual feedback was deemed to have the capacity of disturbing the other dancers or festival goers (e.g., *"The vibrations were more personal and you feel them directly. The lights can annoy people around, plus I might not see them, when my hand is not in front of me"*).

The participant who preferred the visual feedback motivated the choice with the fact that visual feedback is less distracting (e.g., *"Not as distracting, but that might be the point I guess"*), while the participant who preferred the multisensory feedback attributed the reason to personal aesthetic judgments (e.g., *"It was very cool to have mix of both"*).

Concerning the question about the type of sensory feedback preference during a real world use of the device, 8 out of 13 participants preferred the haptic feedback condition (whereas none preferred the visual only condition, and five preferred the visual-haptic one). A significant one-tail binomial test showed that this amount is different from the null hypothesized value of probability of the chance level, i.e., 0.333 ($p < 0.05$, 95% confidence interval: [0.35, 1.0]). For the visual condition the binomial test turned to be significant ($p < 0.001$), whereas it was not significant for the visuo-haptic condition (see Fig. 3c).

Concerning the reasons for choosing the haptic feedback in a real world situation, participants expressed the similar statements as those reported above. On the other hand, two participants who reported the preference for the visuo-haptic feedback motivated their choice with the fact that the feedback combination is stronger than the haptic or visual alone (e.g., *"In a chaotic festival situation, I imagine the visual feedback could be useful too, both feedbacks will be needed when listening to high intensity music in order to actually detect the signal"*). Furthermore, participants commented on the aesthetic qualities of a bracelet having also visual feedback (e.g., *"The light is nice and the haptic feedback actually gets your attention. The combination also makes feel more like a festival gadget than just a health thing"*).

Figure 3d–f respectively show the results for the questionnaire items Experience, Clarity and Effectiveness. A Kruskal-Wallis test did not reveal any significant main effect between the three feedback conditions.

The majority of participants, namely 10, reported to not use any hearing protection during loud music events. Only 3 reported to use earplugs (either in foam or more sophisticated material).

Concerning the question on the expected concrete use of BrrraceLED at loud music events, 6 participants reported that they would not use BrrraceLED. For four participants, this was due to the fact that they would rather use the earplugs (e.g., *"No, because I come to these situations with the expectation that it will be loud, and therefore prepare myself with earplugs."*). The answer of the other two participants instead showed that for them the device would not be useful as they do consciously choose to go to the loud music environments (e.g., *"I do not see myself wearing this. If I am going to a festival I assume there will be loud music and it does not bother me. I am okay with noise."*). The same concepts were expressed by other two participants in the open comments (e.g., *"Maybe people are aware that their environment dam-*

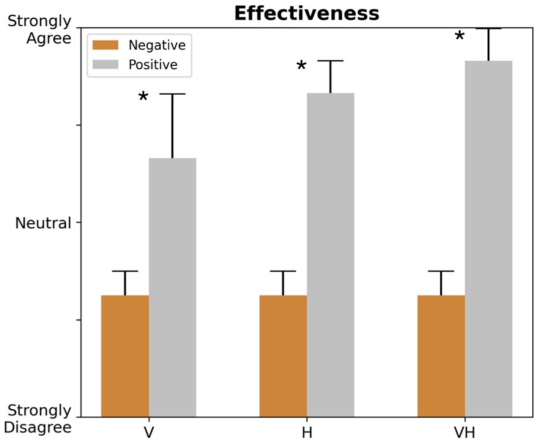

Fig. 4 Mean and standard error of the questionnaire item Effectiveness for participants who reported to have an attitude towards hearing health that was negative (orange) and positive (gray). Legend: V = visual, H = haptic, VH = visuo-haptic; * = $p < 0.05$

ages the hearing but they don't care?"; "People who love going to festivals rarely will drop them if the noise is too loud. For some, that's one reason to go to them.").

On the other hand, 7 participants stated that they would use the device (e.g., *"Yes, since it is comfortable and has a lot of benefits for our health"; "I would try it. Sometimes you don't even notice how loud it was until you leave and your ears are just buzzing"; "Depending on my current situation, if I go to a festival I know that the music is going to be loud, but with the bracelet I can go at the back of the crowd."*).

Based on these comments, to further investigate the perceived effectiveness and usefulness of our device, participants were split into those who clearly declared to have a positive attitude towards hearing health (the 3 participants who reported to use earplugs and care about their hearing) and those having a negative attitude towards it (the 4 participants who stated to enjoy loud music). The participants who did not report a clear statement about this aspect were not included. As shown in Fig. 4, the average evaluations are higher for the positive group compared to the negative group for all feedback conditions. The statistical analysis, conducted with a Wilcoxon rank sum test, revealed that all such differences are significant (W = 0, $p < 0.05$).

6 Discussion

The results of the experiment showed that all participants actually noticed the three kinds of feedback in all experimental sessions. The reactions times, however, significantly differ. As illustrated in Fig. 3a, visual feedback led to the slowest reaction times compared to the haptic and visuo-haptic conditions. No significant difference was found for haptic versus visuo-haptic conditions, although the latter led on average to the fastest reaction times. This is in line with the fact that the temporal resolution of the sense of touch (in the wrist area) is higher than that of the visual system [44]. An additional plausible explanation for this result is that participants would need to be actively looking at the bracelet in order to detect the LED strip, whereas haptic feedback can be detected passively without having to pay any particular attention. Nevertheless, in the actual context of use of the bracelets, even the reaction times in presence of the visual-only feedback (less than 3 s) are sufficient to notify the user about the harmful condition due to the loud sound.

Participants clearly manifested their preference for the haptic or the visuo-haptic feedback rather than the visual one, both during the experiment and for the envisioned use in a real world scenario. Visual feedback alone would not be as strong as the haptic or visuo-haptic counterparts in signalling the notification about the loud music condition. Yet visual feedback could be a working complement to the haptic feedback alone since in presence of very loud music (not the case of the present experiment) vibrations of low frequency sounds propagate in the whole body thus potentially masking the effect of the bracelet.

Nevertheless, Fig. 3f shows that for all three sensory conditions participants were fairly neutral about the effectiveness of the device in terms of them avoiding loud places if it was to provide feedback on the sound levels. This highlights the issue that users may not actually take a technology feedback on board and act upon it. In line with this quantitative result, the participants' comments revealed that there may be a cultural problem preventing the use of the BrrraceLED, which has nothing to do with its effectiveness, i.e., the fact that clubbers and festival goers deliberately choose to go to these events because of the loud music. Sounds at levels that can injure the ear are regarded as enjoyable by many people [18]. Different studies have shown that increasing numbers of people, particularly adolescents and young adults, are exposing themselves to music on a voluntary basis at potentially harmful levels, and over a substantial period of time, which can cause noise-induced hearing loss [18, 20]. Our study also clearly shows that a non negligible portion of the involved participants like to be exposed to high sound levels, and in most cases seem not interested in the damage that can likely be caused to the hearing system. Therefore, whilst solutions like BrrraceLED might help to alert people to noisy situations, the real problem is changing people's attitudes and motivations to want to protect their hearing.

Health educators, especially those dealing with adolescents, typically face the difficult task of dealing with the deliberate exposure to loud music or the barriers to the use of hearing protection (such as enjoying loud music [18]). Several authors have warned about the need for more education regarding the risks of loud music exposure and the benefits of wearing hearing protection, for more hearing protection use by those at risk, and for more regulations limiting music intensity levels at music entertainment venues [20, 45, 46]. As suggested in [24], health promotive strategies should focus on changing not merely individual attitudes, but also societal norms and regulations in order to decrease noise induced auditory symptoms among adolescents, and this may be extended to older individuals. Moreover, the study reported in [47] proposed some additional targets for intervention, such as by improving motivation. This aligns with our findings about BrrraceLED being judged as ineffective at prompting behaviour change (i.e., avoiding noisy situations). Nevertheless, other authors have suggested that effective prevention strategies to avoid music-induced hearing loss among adolescents due to discotheque attendance need to be taken primarily by discotheque owners and disk jockeys [48].

It is worth noticing that while our system was primarily conceived to support hearing loss prevention for those who attend loud music events, it can find application in a number of other scenarios and for other stakeholders. For instance, the bracelet or a smartwatch with a dedicated app could be useful to parents who may unconsciously expose their children to harmful high sound levels (e.g., during concerts, parades, etc.). The bracelet could be used by employees of music clubs [49] to monitor their exposure through time. The system could be particularly useful to all those who work with their ears such as disc jockeys [50], sound engineers [51], and other music professionals [52]), as well as to the visually-impaired population, for whom the auditory sense is extremely important. Moreover, it is known that some individuals with autism spectrum disorder have difficulties in coping with high sound intensities [53], and there are a number of individuals who are very sensitive to loud sounds [54].

It is also worth noticing that our study presents some limitations. First, the evaluation of the prototype was conducted with a restricted number of participants. Nevertheless, this was statistically sufficient to investigate the aspects under study. Second, although the evaluation was conducted in ecologically-valid conditions, it was still a controlled setting where users were aware to have to perform a task. An in-the-wild investigation [55] would provide further insights on the adoption of the technology in the long run by the target population.

7 Conclusion

Repeated exposure to loud music carries the concrete and probable risk to cause noise-induced hearing loss, which nowadays is an important health concern. Our study investigated the use of a multisensory interactive system as a means to warn users when the music sound level is too loud in their specific location. Specifically, the use of visual and haptic feedback was devised to provide information through the free sensory channels of vision and touch. Our study also aimed at providing further insight into the potential risk of hearing loss caused by exposure to loud music especially in the young population, and thus contributing to further raising awareness of music induced hearing loss.

Results showed that participants never missed the notification via all types of feedback, but visual feedback led to the slowest reaction times and was deemed the least effective. In line with the findings reported in the hearing loss prevention literature, the perceived usefulness of the proposed device was highly dependent on participants' subjective approach to the topic of hearing risks at loud music events as well as their willingness to take action regarding its prevention. Ultimately, our study has shown how technology, no matter how effective, may not be able to cope with these kinds of cultural issues concerning hearing loss prevention. Educational strategies may represent a more effective solution to the real problem of changing people's attitudes and motivations to want to protect their hearing.

In future work we plan to create a miniaturized version of the prototype and to connect it to an app for smartphone enabling the monitoring of the frequency and duration of the exposure to loud sounds. We aim at extending the prototype with a control allowing the user to modify the sound level threshold for the activation of the feedback (which may be useful when the user is wearing earplugs). Moreover, we plan to create an app for smart watches, thus leveraging existing hardware able to measure environmental sound and provide visuo-haptic feedback. Furthermore, we plan to conduct in-the-wild studies to assess the effectiveness of the system in real world scenarios.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent to participate All participants signed written informed consent prior to the experiment.

Consent for publication All authors give their consent for publication.

Ethics approval The experimental procedure was in accordance with the rules set by University of Trento Ethical Committee.

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