Musical Haptic Wearables for Synchronisation of Visually-impaired Performers: a Co-design Approach

Luca Turchet
Department of Information Engineering and Computer Science
University of Trento
Italy
luca.turchet@unitn.it

David Baker
Institute of Education
University College London
United Kingdom
david.baker@ucl.ac.uk

Tony Stockman
Centre for Digital Music
Queen Mary University of London
United Kingdom
t.stockman@qmul.ac.uk

Figure 1: Blind musicians playing together using the armband-based musical haptic wearables.

ABSTRACT

The emergence of new technologies is providing opportunities to develop novel solutions that facilitate the integration of visually-impaired people in different activities of our daily life, including collective music making. This paper presents a study conducted with visually-impaired performers, which involved a participatory approach to the design of accessible technologies for musical communication in group playing. We report on three workshops that were conducted together with members of an established ensemble of solely visually-impaired musicians. The first workshop focused on the identification of the participants' needs during the activity of playing in groups and how technology could satisfy such needs. The second and third workshops investigated, respectively, the activities of choir singing and instrument playing in ensemble, focusing on the key issue of synchronisation that was identified in the first workshop. The workshops involved prototypes of musical haptic wearables, which were co-designed and evaluated by the participants. Overall, results indicate that wireless tactile communication represents a promising avenue to cater effectively to the needs of visually-impaired performers.

IMX '21, June 21–23, 2021, Virtual Event, NY, USA

ACM ISBN 978-1-4503-8389-9/21/06…$15.00
https://doi.org/10.1145/3452918.3458803

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *Empirical studies in accessibility*; Accessibility technologies.

KEYWORDS

Musical Haptic Wearables, visually-impaired performers, Internet of Musical Things, musical haptics, accessibility

ACM Reference Format:

Luca Turchet, David Baker, and Tony Stockman. 2021. Musical Haptic Wearables for Synchronisation of Visually-impaired Performers: a Co-design Approach. In *ACM International Conference on Interactive Media Experiences (IMX '21), June 21–23, 2021, Virtual Event, NY, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3452918.3458803

1 INTRODUCTION

In recent years, there has been increasing interest in wearable devices encompassing haptic stimulation and targeting music performers [6, 16, 23, 33]. This endeavor falls within the remits of the emerging field of *musical haptics*, which relates to the application of haptics research to the musical domain [24]. Works in this field has included the development of haptic interfaces not only for music performers (e.g., haptically-enhanced digital musical instruments [19, 34] or tactile notification systems [12, 15, 27]), but also for music listeners (e.g., haptic devices aiming to enrich the musical listening experience [21, 32]).

A related strand of research has prioritised accessibility aspects related to visually-impaired musicians, which represents an important aspect for social inclusion of this section of the worldwide population [3, 4]. Various devices have been developed to support visually-impaired musicians in various activities. This includes haptic tools for studio production (e.g., haptic waves, a device that allows cross-modal mapping of digital audio to the haptic domain [28]), systems for interactions between conductors and blind choristers [11], and haptic wearables for integrating visually-impaired musicians in orchestras of sighted musicians (e.g., [2, 18]). A successful methodology involved in some of these studies is participatory design [22, 26, 28], where the haptic devices are designed together with the visually-impaired musicians through an iterative process.

The advent of embedded and networking technologies has set the stage for the creation of new wearable devices for creative communication in musical contexts by leveraging the tactile channel. Recently, the *Musical Haptic Wearables (MHWs) for performers* have been proposed as instances of a wider family of Musical Things [29] within the Internet of Musical Things (IoMusT) paradigm [30]. Such a class of wearable devices targeting music performers encompasses haptic stimulation, gesture tracking, and wireless connectivity features. MHWs were conceived to enhance creative communication between performers as well as between performers and audience members by leveraging the sense of touch in both co-located and remote settings. MHWs can be utilised to support musical communication among visually impaired performers (see e.g., [1]). Nevertheless, to date, this line of research has been scarcely addressed despite its potential to greatly benefit blind performers.

In this paper, we report on three workshops conducted with an ensemble of solely visually-impaired performers, following a participatory design methodology. Our work investigated the challenge of synchronisation among visually-impaired musicians, a central issue which emerged during the workshop. In contrast to other studies that investigated how to convey to visually-impaired musicians visual information related to the gestures of a sighted conductor (e.g., [2]) our work involved only non-sighted musicians. We investigated two scenarios, choir singing and playing in ensemble, where the conductor was one of the members of the group empowered with a dedicated controller. We show the results of preliminary evaluations of MHW prototypes which highlight the potential of this technology to make collaborative music making more inclusive.

2 METHOD

Our methodology was partly inspired by that reported in [28], and consisted of three workshops, which spanned a period of three months. They comprised the following activities:

- **Workshop 1:** meeting users, initial problem identification, technology demonstration, brainstorming;
- **Workshop 2:** co-design, testing and gathering feedback from an initial low-fi prototype for choir singing;
- **Workshop 3:** co-design, testing and gathering feedback from an initial low-fi prototype for instrument playing.

We worked with nine visually-impaired musicians (seven men, two women) through the series of activities. Participants were recruited from the "Inner Vision Orchestra", a London-based ensemble of thirteen blind musicians[1]. The music of this ensemble moves between songs from Iran, Lebanon, Afghanistan, India, Nigeria, to soulful Gospel and Blues to Indian Ragas and Western Classical compositions. The musicians use a wide variety of musical instruments from traditional folk music to classical music (see Figure 1), and all of them also sing.

Some participants took part at the beginning, but were not available for later activities, while others joined at the second or third workshop. From the nine total, there were three who took part in all of the activities listed above. All participants reported not to have had any previous experience with haptic technologies for musical communication similar to those investigated in this study.

3 FIRST WORKSHOP

We organised a half-day scoping workshop and invited a group of seven of our users (five males, two females) from the Inner Vision Orchestra. The aims of this workshop were manifold: i) to meet the community we were working with; ii) to find out their existing methods of playing together; iii) to identify problems they experience while playing together; iv) to introduce new technologies in the form of mock ups; v) to brainstorm ideas for possible new solutions. This procedure was intended to create an harmonious and relaxed atmosphere among the group, foster a dialogue about potential problems and then introduce the participants to novel technologies. It was then hoped that in the final part of the workshop, the participants would be inspired by the technologies to suggest design ideas that we could work with.

3.1 Identified needs

Participants reported that they played mostly among themselves or with other blind musicians, and rarely in ensembles of sighted and non-sighted musicians. Therefore, in our investigations we directed our attention to the case of playing in ensembles of solely visually-impaired musicians.

Participants described enjoying playing music together in two main scenarios: choir singing and instrument playing. Both these scenarios did not involve a sighted conductor. To play together participants reported that they relied on their memory of the score to be played as well as on vocal remarks to guide rehearsals provided by one member of the ensemble who acted as a conductor. Participants identified a broad range of issues they encountered in the tasks of playing together during these two scenarios. These included the directions about when a musician had to start and stop playing, or when s/he had to increase or decrease the volume and the tempo. Nevertheless, the most pressing of the identified issues were timekeeping and synchronization with other fellow musicians.

3.2 Technology demonstrations and brainstorming results

To create a demonstration of interfaces that could provide vibrotactile cues useful to direct visually-impaired musicians during their practices, we let participants experience various MHWs that were developed in previous research (reported in [29] and [32]). These consisted in a belt equipped with four motors (see Figure 2a), a single self-contained armband equipped with two motors and two buttons (see Figure 2b), and a pair of armbands both equipped with two motors (see Figure 2c).

[1] http://balujimusicfoundation.org/about_us/inner-vision.php

a) belt b) self-contained armband c) double armband

Figure 2: The MHWs prototypes involved during the technology demonstrations: a) a belt equipped with four motors; b) a self-contained armband equipped with two motors and two buttons; c) a pair of armbands both equipped with two motors.

Each participant could wear and interact with the developed prototypes and experience the various vibration patterns that were designed by the authors. Subsequently, participants were asked to describe their impressions when interacting with the technology.

The belt was found impractical due to the fanny pack and to the position that was found to be uncomfortable during the act of playing. The self-contained armband was deemed too cumbersome and heavy, as well as the fact that the buttons were found difficult to reach and use while singing and playing. The double armband was found to be the MHW most appreciated. This was due to its lightweight and to the fact that two distinct sources of vibrations could encode more information. However, also in this case the involved fanny pack was deemed to be obtrusive.

Moreover, participants suggested that the wearables could have been placed in parts of the body different from those investigated during the initial phase of the workshop. They also suggested that the position and shape of a MHW could vary according to the instrument played. Therefore, we let participants freely explore other positions and shapes of a potential wearable interface. For this purpose, we re-used the double armbands prototype given the fact that it could be flexibly reconfigured. The new positions (see Figure 3) included the placing of the prototype strips on i) various parts of the arms and of the forearms; ii) on the back; iii) on the wrist and arm; iv) on both legs; v) on both wrists. To accomplish these positions and let workshop participants experience the vibrations in the most effective way, we used scotch tape and clips that secured the motors to the participants' clothes or skin.

After having tried each position extensively and various kinds of vibration patterns [9], the consensus was that the best position for the activity of choir singing was the central part of the arm and that for the activity of playing instruments was the wrist, independently of the played instrument. Furthermore, participants suggested that to deliver the musical directions to the other musicians a device was needed and could be utilised by one of the musicians not playing but acting solely as a director. Most of the participants were familiar with electronic music technologies such as MIDI controllers and therefore they suggested to use a device of that kind.

4 SECOND WORKSHOP

The second workshop aimed at testing an improved prototype of MHW based on the armband, for the activity of choir singing. The workshop also aimed at further investigating the musicians' needs for synchronisation while singing together as well as co-designing the vibrations. Six participants took part in this workshop, which lasted half a day.

4.1 Prototype

Nine MHWA prototypes were created to provide tactile stimuli on both arms, but during the workshop we used only six, one for each participant (see Fig. 4b). At hardware level, the prototype improved the armband-based MHW presented in the first workshop by substituting the fanny pack with a small and lightweight plastic box that contained the hardware. This box had a hook that allowed participants to secure it to their trousers if wished. Otherwise, the box could be placed on the chair on which musicians sit, thanks to long wires connecting the box to the motors encompassed in the two elastic armbands.

In more detail, the hardware components consisted of the Bela board [20]; a Wi-Fi USB dongle compatible with the IEEE 802.11ac standard exploiting the 5GHz band; four vibration motors (i.e., PWM-controlled eccentric rotating masses), two for each armband (these particular motors were chosen for their capability of providing a wide range of dynamics given a maximum vibration amplitude of $7g$, and quick rise and decay time, 28 ms and 49 ms, respectively); a lightweight power supply.

At software level, data processing and synthesis of the tactile stimuli were accomplished using Pure Data applications leveraging the Pulse Width Modulation (PWM) technique. The same applications implemented data reception and forwarding through Open Sound Control (OSC) messages over UDP. The measured average latency and jitter of the local network (one way, not roundtrip) were 1.7 ms and 0.66 ms, respectively. In addition, to implement clock synchronisation of all MHWs we leveraged the Ableton Link protocol [13].

In addition to the MHWs prototypes we used a nanoKONTROL2 MIDI controller by Korg (see Fig. 4a). This was connected to a Bela board encompassed, together with a battery and a Wi-Fi dongle, in

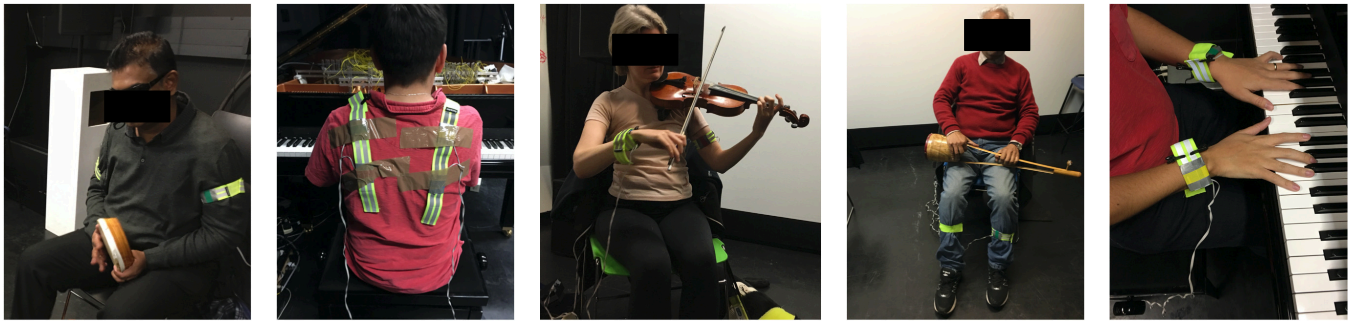


Figure 3: Position of the MHWs on various body parts explored during the workshop. From left to right: both arms, back, wrist and arm, both legs, both wrists.

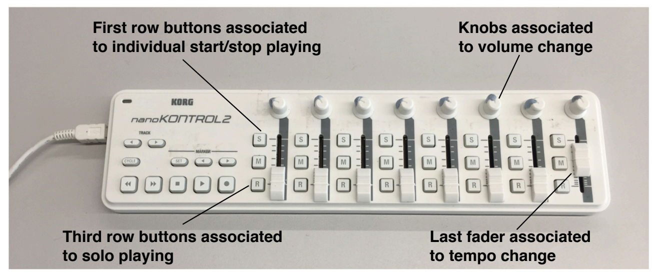
a plastic box similar to that involved for the MHWs. In this way a portable device was created. This device was designed to allow the conductor to deliver the musical directions to the ensemble members, by controlling faders, knobs and buttons. The values of those controls, wireless transmitted to the MHWs in the form of OSC messages, were associated with a certain musical direction. In particular, the rightmost fader of the MIDI controller was mapped to the beat message of the Link protocol, to continuously control the tempo of the performed piece.

4.2 Procedure

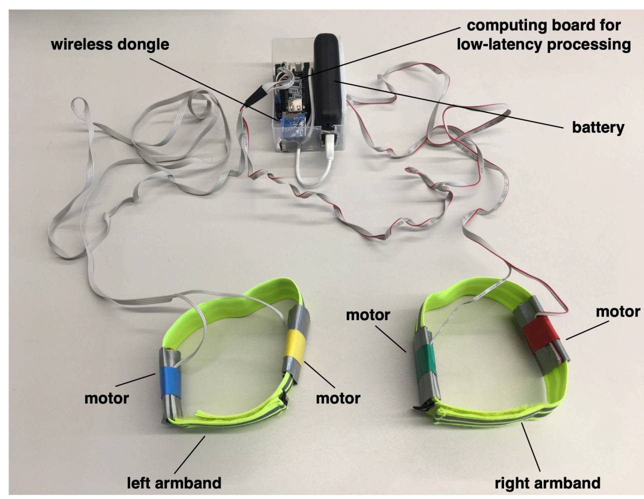
The second workshop concentrated mainly on the investigation of the timekeeping and synchronisation issues reported by participants during the first workshop. Specifically, we focused on one piece in 4/4 composed by the ensemble, in which each member had to start singing every two bars and had to stop singing after two bars. This entrance and exit followed a circular structure and the piece could last ad libitum. Participants reported to have issues in detecting the precise moment in which to enter and exit as well as in unwanted fluctuations in the tempo.

To cope with these issues we asked participants to co-design the vibrations they wanted to receive on both of their arms. The experimenter coded on the fly the software embedded in the MHWs according to the participants' indications. After a series of trial and errors, a consensus was found for a final design. This consisted in assigning to the dominant arm a vibration pulsing at regular intervals according to the tempo established by the conductor, and assigning to the non dominant arm a set of four vibrations, synchronised with those received by the dominant arm, that preceded the moment when the participant should start or stop singing. In more detail, since the piece was in 4/4, the stronger beat was accentuated compared to the other three, by increasing the intensity of the vibration (i.e., augmenting the "on phase" of the motor in the PWM duty cycle). The intensity level of the two types of vibrations was regulated following the participants preferences, by allowing them to adjust the related control values.

To test the resulting design, the experimenter played the role of the director using the MIDI controller. The test consisted firstly of two trials in which participants sung the composition at 80 beats per minute (BPM), and secondly a further two trials in which the experimenter slowly moved the fader to accelerate and decelerate the tempo in the range of 60 - 100 BPM. Each trial lasted about two minutes. Before starting the actual tests a familiarisation trial was conducted. At the end of the test participants were asked to comment on their experience. These trials were videorecorded for further analysis at behavioral level by observing how participants interacted with the technology.



a) MIDI controller



b) MHW prototype

Figure 4: The developed prototypes for transmission and reception of haptic messages with indications of their main components. a) the MIDI controller; b) the armband-based musical haptic wearable.

Table 1: The mappings between the MIDI controller controls and the vibrations produced by the MHWs.

Control	Musical direction	Type of vibration
Buttons in the first row	Start/stop playing	Strong vibration lasting 2 seconds on both left and right wrist
Buttons in the third row	Solo playing	Intermittent pulses alternating between left and right wrist for 5 seconds
Knobs	Volume change	Intermittent pulses on both wrists with intensity proportional to the slider value
Rightmost fader	Tempo change	Intermittent pulses on both wrists happening at the selected BPM

4.3 Results

The behavioral analysis conducted by deeply scrutinizing the videorecordings clearly showed that participants could sing together with an excellent level of synchronisation thanks to the provided devices. In particular perfect entrances and exits of each singer were found in all trials.

The comments of participants was enthusiastic. They unanimously reported that the device was effective in improving the timing of their entrances and exits, as well as that it allowed them to keep the tempo. Moreover, tempo accelerations and decelerations were found to be easy to follow, although participants also commented that such temporal variations had to happen slowly. When asked if they preferred singing with or without the MHWs, participants' response were unanimous in favor of the former. The collectively designed vibrations and their delivery places were found to be appropriate during the actual usage of the devices while singing, and were deemed to not interfere with the expressive intents of the singers.

Nevertheless, this full consensus on the validity of the proposed approach was contrasted by the consideration, reported by all participants, that a longer training period would have benefitted them to get more confidence with the device. A high level of familiarity with the technology was deemed crucial in particular for actual live performances scenarios. A risk reported by one participant related to the habituation factor, that is after a prolonged and constant usage participants could get accustomed to the presence of the vibrations and somehow tend to ignore them. To avoid this, the participant reported that the vibrations should occur only in presence of the actual singing practice and stop during the pauses of the rehearsals or concerts.

5 THIRD WORKSHOP

The third workshop was attended by five musicians, and lasted half a day. The goal of the workshop was to co-design and test vibrations provided at the participants' wrists during their act of playing an instrument in the ensemble. For this purpose a MHWs bracelet was created, which was based on the elastic strips, hardware and software used in the MHWs involved in the second workshop. Each participant wore a bracelet on each wrist. The third workshop not only investigated synchronisation and timekeeping issues, but also other musical directions such as starting and stopping playing, and changing volume. Furthermore, the workshop aimed at studying the participants' experience in interacting with the MIDI controller when playing the role of director. The evaluation experiment was video-recorded for further analyses.

5.1 Procedure

Similarly to the second workshop, we involved the participants in co-design activities. Specifically, they co-designed both the vibrations of the haptic bracelet and the mapping between such vibrations and the controls of the MIDI controller (i.e., knobs, faders and buttons). The result of these mappings is illustrated in Figure 4a and is summarised in Table 1. All controls were assigned to individual members, with the exception of tempo change, which was applied to all members when the rightmost fader was modified. The designed tempo was 4/4 and involved the same kind of vibrations that were co-designed in the second workshop.

Subsequently, each participant took turns to play the role of the conductor, using only the MIDI Controller, as well as the role of musician guided by the conductor. When using the MIDI controller the participants did not wear the MHW. In this phase they could play pieces of music of their own choice (each piece was in 4/4).

After all participants had practiced with the system they were asked to answer to questions of a questionnaire, which was partially based on the System Usability Scale questionnaire [8]. The questionnaire comprised the following questions to be evaluated on a 5-point Likert scale (1 corresponds to *strongly disagree* and 5 stands for *strongly agree*):

- *[Frequency.] I think that I would use this system frequently.*
- *[Complexity.] I found the system complex to use.*
- *[Irritation.] I thought the vibrations were irritating.*
- *[Quick learning.] I would imagine that most blind musicians would learn to use this system very quickly.*
- *[Confidence.] I felt very confident using the system.*
- *[Slow learning.] I needed to learn a lot of things before I could get going with this system.*
- *[Satisfaction.] I was satisfied with the results I got out of the system.*
- *[Usage.] I would be happy to use this system on a regular basis.*
- *[Enjoyment.] I enjoyed using this system.*
- *[Recommendation.] I would recommend this system to a fellow blind musician.*

Questions were provided vocally by the experimenter, simultaneously to all five members of the ensemble. Participants were asked to answer by indicating the number with the fingers of their dominant hand. After the questionnaire, participants were invited to leave an open comment and to discuss, in a focus group format, about the experience of interacting with the system.

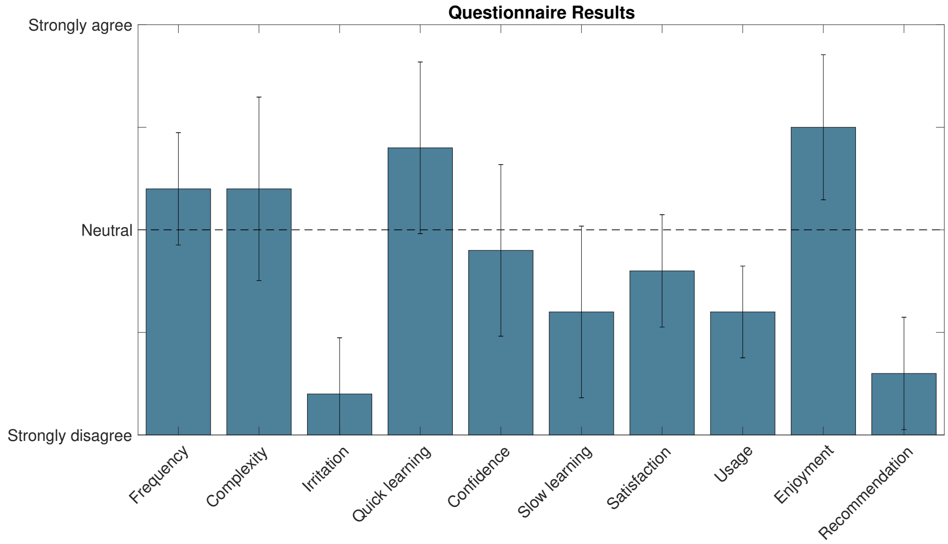


Figure 5: Mean and standard deviation of the questionnaire items (evaluated on a 5-point Likert scale).

5.2 Results

The analysis of the videorecordings provided insights on the actual interaction of the musicians with the technology. In general participants were able to precisely time their playing to the vibrations although this occurred only for some minutes (ranging from about 1 up to a maximum of 4.30). Indeed at some moments some of the participants lost the synchronicity causing, after a few seconds, the whole ensemble to interrupt and start again. Inspection on the auditory results also revealed that participants could always start perfectly in synch after the agreed number of beats preceding the beginning of the piece. Moreover, during the first minutes some of the participants tended to be more precise in terms of coupling their musical outputs to the time compared to the last minute before losing the synch. This phenomenon was accentuated when the tempo variations occurred. This inability to keep the time for longer periods may be due to the increase of cognitive load caused by the simultaneous needs of following the vibrations, the required distributed attention towards the other musicians' outcomes, and individual expressivity intents. This could be coupled with the interacting factor that a longer time to get acquainted with the system while playing in ensemble is needed.

Figure 5 illustrates the results of the questionnaire items. The system was not deemed particularly difficult to use or to learn. Vibrations were not found to be irritating while playing an instrument, and participants reported to have enjoyed the experience of interacting with the system. However, they also reported not to have felt very confident with the system, and not particularly satisfied by their usage. As a consequence participants did not feel they would use this specific version of the system on a regular basis and would not recommend it to peers.

The findings from these quantitative results were complimented by the qualitative open comments participants provided. Participants' comments were analysed in the video recordings using an inductive thematic analysis [7]. The analysis was conducted by generating codes, which were further organised into themes that reflected patterns, as described below.

Utility. All participants consistently reported that the MHW concept has the concrete potential to effectively help them in the task of starting/stopping playing, modifying volume and tempo, and keeping the time while playing their instruments in the ensemble. Nevertheless, the current version of the prototype was deemed not mature enough to support in a fully effective way the communication needs while playing.

Ergonomics. Three participants felt limited in the interaction possibilities afforded by the system, requesting more features. Firstly, they reported that the main issue at interaction level was that the developed bracelet was too cumbersome and a smaller and lighter version would have benefitted their interaction. Moreover, they indicated that the wires partly hindered their freedom of movement, highlighting the need for a fully wireless system. They suggested to use commercially available bracelets or similar systems integrating haptic motors, like the Apple Watch.

Inclusiveness. Consistently, all musicians deemed that thanks to the developed system it would be easier to integrate non-sighted musicians in ensembles of sighted musicians. They also highlighted the importance of technological advancements in musical communication for social inclusion of blind musicians. They pointed at the fact that despite examples of successful visually impaired musicians in the musical industry, the musical industry is not yet very alive to the potential of visually impaired musicians or in general particularly accessible to them.

Training period. Whereas in general participants stated that the system's functionalities and behaviors were quick to learn, four participants reported that a longer familiarisation phase would have benefitted their performances during the testing of the system. This impacted both the use of the MIDI controller and of the MHWs. Participants pointed at the need of having the devices at home in order to get more acquainted with it and practice before running validation experiments.

6 DISCUSSION AND CONCLUSION

This paper presented three workshops conducted with visually-impaired performers, which involved a participatory approach to the design of accessible technologies for musical communication in group playing. Two scenarios were investigated, choir singing and instrument playing in an ensemble, which both involved only non-sighted musicians.

At system level, our approach differed from that of other systems developed for similar purposes. Most of previous systems involved the tracking of the tempo from the gestures [11] or the movements of the baton of the conductor [2, 18], whereas in the current study we involved a MIDI controller and a system based on the Ableton Link protocol to synchronise the BPM of vibro-tactile devices across a local wireless network.

Whereas reactions of participants were generally enthusiastic towards the concept and the developed technology, the study also revealed some limitations. Firstly, the developed technology was not mature yet. Despite the involvement of participants in the process of designing both the communication system and the vibration patterns produced by the devices, technological issues were found which hindered more successful interactions with the system and its future adoption. Therefore, more research is necessary to progress the technological aspects of the system towards a more robust set of prototypes, as well as more iterations with participants being required to address their needs more satisfactorily.

Secondly, in both the second and third workshop, some participants reported the need for time to get used to the vibrations and associate the vibration patterns with the corresponding musical directions. As a consequence of this, they also said that after a longer training period they could have been more efficient in responding to the musical directions. Notably, this need for a longer time to get familiar with and responsive to the tactile cues parallels the findings reported in other studies in musical haptics [3, 14, 32].

However, it is worth noticing that our study has some limitations. Firstly, a small sample size was involved and musicians were not highly trained nor professionals, who could try the system only for a limited amount of time. Secondly, a restricted number of musical instruments, tempi, and genres were investigated. Thirdly, all participants came from the same, unique ensemble, whereas more ensembles would be needed to properly study the actual application of the MHWs under different conditions. Fourthly, the co-design exercises focused mainly on the design of the vibration intensities and a restricted number of vibration patterns, along with the selection of the area of the body impacted by the source of the vibrations. Co-design activities accounting for a wider scope of the design variables could provide other useful insights.

Nevertheless, despite these limitations we believe that the preliminary results presented in this paper are useful to provide directions to designers of MHWs for visually-impaired performers. The adoption of the Ableton Link protocol appears a promising avenue for ensuring vibrotactile synchronisation for small ensembles of visually-impaired musicians [31]. Notably, throughout the workshops participants demonstrated an enthusiasm for haptic interaction. The feedback we received from users encourage us to move forward to make a fully functioning hi-fi prototype. The devices were developed in an iterative, participatory manner showing the value of adopting a user-centered design approach when creating technologies for visually-impaired musicians.

Future directions include making the MHWs more compact, by using smaller components that can be embedded in the wearable itself so to avoid any trailing wires. Moreover, in future work we plan to run additional experiments involving different ensembles, more pieces, different kinds of music genres, so to test extensively the MHWs concept in various scenarios. We also plan to increase the number and the complexity of the interactions afforded by the system. Furthermore, we are looking into studying the learning curve of the interface through a longitudinal study to determine the level of training necessary for visually-impaired performers to achieve sufficient proficiency. Such a longitudinal study will also help reveal any potential issues such as adaptation to the tactile stimuli.

Notably, the developed systems have implications for synchronisation of geographically displaced visually-impaired musicians, connected via networked music performance systems [10, 25, 30] involving dedicated metronomes a [5, 17]. These avenues will also be investigated in our future works.

The emergence of new technologies is providing opportunities to develop novel solutions that facilitate the integration of visually-impaired people in different activities of our daily life, including collective music playing. It is the authors' hope that this work could contribute to promote research on accessibility topics related to music playing. It is also hoped that this work could contribute to address any imbalance that is identified by the absence of blind and visually impaired musicians in most music industry activities.

7 ACKNOWLEDGMENTS

The authors wish to thank the members of the Inner Vision Orchestra who took part in the workshops.

REFERENCES

[1] T. Asakawa and N. Kawarazaki. 2012. An electric music baton system using a haptic interface for visually disabled persons. In *Proceedings of the SICE Annual Conference*. IEEE, 602–607.

[2] J. Bajo, M. A. Sánchez, V. Alonso, R. Berjón, J. A. Fraile, and J. M. Corchado. 2010. A distributed architecture for facilitating the integration of blind musicians in symphonic orchestras. *Expert Systems with Applications* 37, 12 (2010), 8508–8515.

[3] D. Baker, A. Fomukong-Boden, and S. Edwards. 2019. "Don't follow them, look at me!": Contemplating a haptic digital prototype to bridge the conductor and visually impaired performer. *Music Education Research* 21, 3 (2019), 295–314.

[4] D. Baker and L. Green. 2017. *Insights in Sound: Visually Impaired Musicians' Lives and Learning*. Taylor & Francis.

[5] R. Battello, L. Comanducci, F. Antonacci, A. Sarti, S. Delle Monache, G. Cospito, E. Pietrocola, and F. Berbenni. 2020. An Adaptive Metronome Technique for Mitigating the Impact of Latency in Networked Music Performances. In *2020 27th Conference of Open Innovations Association (FRUCT)*. IEEE, 10–17.

[6] A. Bouwer, S. Holland, and M. Dalgleish. 2013. The Haptic Bracelets: learning multi-limb rhythm skills from haptic stimuli while reading. In *Music and human-computer interaction*. Springer, 101–122.

[7] V. Braun and V. Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101.

[8] J. Brooke. 1996. SUS–A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.

[9] J.R. Cauchard, J.L. Cheng, T. Pietrzak, and J.A. Landay. 2016. ActiVibe: design and evaluation of vibrations for progress monitoring. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 3261–3271.

[10] L. Gabrielli and S. Squartini. 2016. *Wireless Networked Music Performance*. Springer. https://doi.org/10.1007/978-981-10-0335-6_5

[11] C. Galea and C. Porter. 2018. Accessible choral ensembles for visually impaired singers. In *Proceedings of the 32nd International BCS Human Computer Interaction*

Conference. 1–10.
[12] M. Giordano and M.M. Wanderley. 2015. Follow the tactile metronome: Vibrotactile stimulation for tempo synchronization in music performance. In *Proceedings of Sound and Music Computing Conference*.
[13] F. Goltz. 2018. Ableton Link–A technology to synchronize music software. In *Linux Audio Conference*. 39–42.
[14] E. Gunther and S. O'Modhrain. 2003. Cutaneous grooves: composing for the sense of touch. *Journal of New Music Research* 32, 4 (2003), 369–381. https://doi.org/10.1076/jnmr.32.4.369.18856
[15] L. Hayes and C. Michalakos. 2012. Imposing a networked vibrotactile communication system for improvisational suggestion. *Organised Sound* 17, 01 (2012), 36–44.
[16] S. Holland, A. Bouwer, and O. Hödl. 2018. Haptics for the development of fundamental rhythm skills, including multi-limb coordination. In *Musical Haptics. Springer Series on Touch and Haptic Systems*, S. Papetti and C. Saitis (Eds.). Springer International Publishing.
[17] R. Hupke, L. Beyer, M. Nophut, S. Preihs, and J. Peissig. 2019. Effect of a Global Metronome on Ensemble Accuracy in Networked Music Performance. In *Audio Engineering Society Convention 147*. Audio Engineering Society.
[18] N. Kawarazaki, Y. Kaneishi, N. Saito, and T. Asakawa. 2014. A Supporting System of Choral Singing for Visually Impaired Persons Using Depth Image Sensor. *Journal of Robotics and Mechatronics* 26, 6 (2014), 735–742.
[19] M.T. Marshall and M.M. Wanderley. 2006. Vibrotactile feedback in digital musical instruments. In *Proceedings of the Conference on New Interfaces for Musical Expression*. 226–229.
[20] A. McPherson and V. Zappi. 2015. An Environment for Submillisecond-Latency Audio and Sensor Processing on BeagleBone Black. In *Audio Engineering Society Convention 138*. Audio Engineering Society. http://www.aes.org/e-lib/browse.cfm?elib=17755
[21] S. Merchel and M. E. Altinsoy. 2018. Auditory-Tactile Experience of Music. In *Musical Haptics*, S. Papetti and C. Saitis (Eds.). Springer, 123–148. https://doi.org/10.1007/978-3-319-58316-7_7
[22] O. Metatla, F. Martin, A. Parkinson, N. Bryan-Kinns, T. Stockman, and A. Tanaka. 2016. Audio-haptic interfaces for digital audio workstations. *Journal on Multimodal User Interfaces* 10, 3 (2016), 247–258.
[23] T. Michailidis. 2016. *On the hunt for feedback: vibrotactile feedback in interactive electronic music performances*. Ph.D. Dissertation. Birmingham City University.
[24] S. Papetti and C. Saitis (Eds.). 2018. *Musical Haptics*. Springer, Cham. https://doi.org/10.1007/978-3-319-58316-7
[25] C. Rottondi, C. Chafe, C. Allocchio, and A. Sarti. 2016. An Overview on Networked Music Performance Technologies. *IEEE Access* 4 (2016), 8823–8843. https://doi.org/10.1109/ACCESS.2016.2628440
[26] N. G. Sahib, T. Stockman, A. Tombros, and O. Metatla. 2013. Participatory design with blind users: a scenario-based approach. In *IFIP Conference on Human-Computer Interaction*. Springer, 685–701.
[27] M. Schumacher, M. Giordano, M.M. Wanderley, and S. Ferguson. 2013. Vibrotactile notification for live electronics performance: A prototype system. In *Proceedings of the International Symposium on Computer Music Multidisciplinary Research*. 516–525.
[28] A. Tanaka and A. Parkinson. 2016. Haptic wave: A cross-modal interface for visually impaired audio producers. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2150–2161.
[29] L. Turchet and M. Barthet. 2019. Co-design of Musical Haptic Wearables for electronic music performer's communication. *IEEE Transactions on Human-Machine Systems* 49, 2 (2019), 183–193. https://doi.org/10.1109/THMS.2018.2885408
[30] L. Turchet, C. Fischione, G. Essl, D. Keller, and M. Barthet. 2018. Internet of Musical Things: Vision and Challenges. *IEEE Access* 6 (2018), 61994–62017. https://doi.org/10.1109/ACCESS.2018.2872625
[31] L. Turchet and E. Rinaldo. 2021 (submitted). Technical performance assessment of the Ableton Link protocol. *Journal of the Audio Engineering Society* (2021 (submitted)).
[32] L. Turchet, T. West, and M. M. Wanderley. 2020. Touching the audience: Musical Haptic Wearables for augmented and participatory live music performances. *Journal of Personal and Ubiquitous Computing* (2020), 1–21. https://doi.org/10.1007/s00779-020-01395-2
[33] J. Van Der Linden, E. Schoonderwaldt, J. Bird, and R. Johnson. 2011. Musicjacket – combining motion capture and vibrotactile feedback to teach violin bowing. *IEEE Transactions on Instrumentation and Measurement* 60, 1 (2011), 104–113.
[34] B. Verplank, M. Gurevich, and M. V. Mathews. 2002. THE PLANK: Designing a simple haptic controller. In *Proceedings of the International Conference on New Interfaces for Musical Expression*. 33–36.