Co-design of Musical Haptic Wearables for Electronic Music Performer's Communication

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***Abstract*—Communication between performers is a fundamental aspect in music performance. A large number of electronic music instruments based on tangible and screen-based interfaces require a focused visual attention from performers while they are controlled. In certain stage and artistic configurations, this may be an obstacle to face-to-face creative interactions between co-performers and their collaborators. To address these issues, we adopted a user-centered design methodology to develop a novel class of IoT devices that we term Musical Haptic Wearables for performers. We conducted a co-design workshop with ten electronic musicians using focus-group discussions and the bootlegging technique. This workshop identified numerous creative communication issues between performers in electronic music practice and prepared mock-up prototypes. We then developed three chest-, foot- and arm-worn haptic wearables respectively for co-performer, performer-conductor, and performer-sound engineer interactions. The wearables were assessed with 25 participants using a mixed methods approach. High accuracies (70-100%) were obtained for musical actions expected after instructions wirelessly communicated via tactile signals. The results provide evidence that musical haptic wearables can be an effective medium of communication in the context of electronic music performances. Further challenges were identified regarding size and placement of the devices on the body, interferences with concurrent vibrations generated by music signals, limitations on the range of creative controls, and a required training curve.**

***Index Terms*—Internet of Musical Things, wearables, haptic devices, electronic music ensembles.**

I. Introduction

THE emerging field of *"musical haptics"* investigates the application of haptics research to the musical domain [1]. Endeavors in this field include the development of haptic interfaces for music performers (e.g., haptically-enhanced digital musical instruments [2] or tactile notification systems [3], [4], [5]) and music listeners (e.g., haptic devices aiming to enrich the listening musical experience [6]). Some studies focus on analyzing how haptic cues affect musicians' experience and performance [7], [8], [9], [10].

The Internet of Musical Things (IoMusT) is a novel research field at the intersection of the Internet of Things and Sound and Music Computing, with a particular focus on multisensory facets [11]. It relates to the network of objects and interfaces dedicated to the production, interaction and reception of musical content. Musical Things embed electronics, sensors, data forwarding and processing software, and network connectivity enabling the collection and exchange of data for musical purpose. The advent of embedded and networking technologies sets the stage for the creation of new wearable devices for creative communication in musical contexts by leveraging the tactile channel.

Recently we posited "Musical Haptic Wearables (MHWs) for performers" as instances of a wider class of Musical Things [12]. Such a novel 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.

Communication between performers is a fundamental aspect in music performance [13]. In [14] and [15], the authors discuss communication issues in the practice of electronic music ensembles such as laptop orchestras. Various types of communication infrastructures for networked music performances [16] have been proposed in the laptop orchestra context, namely using wireless local networks [17] with exchange of Open Sound Control (OSC) messages (e.g., [18], [19]). However, as noted by Hayes and Michalakos, *"Often, due to the logistics of performing with laptops, where information is displayed on a sizable screen, and the laptop is usually placed on a table along with peripherals, such as soundcards and controllers, the scope to facilitate gestural anticipation, recognizable visual cues, or meaningful physical movements is much more reduced than with performances using traditional instruments"* [4]. Typical technological solutions to such communication issues have involved exchange of text messages over a local network displayed on the laptop screens [15], especially in the context of live coding [20], [21]. Nevertheless, not all electronic music ensembles are employing only laptops. Devices without screen or networking capabilities may be used instead, such as analog synthesizers, stompboxes, or MIDI controllers. These devices are also used in conjunction with other more conventional musical instruments.

Different authors have advocated the use of haptic stimulation as an alternative to visual display for the communication between players of electronic music ensembles [22], [15], [4], [12]. For instance, by involving the haptic channel in co-performer communication laptop musicians can be free from the constraints of looking at specific parts of the screen to get notifications from other performers [15]. Haptic notifications also enable private communication, an aspect deemed to be desirable as performers may not want the audience to be aware of or understand information exchanged with other musicians or technicians.

A compelling example of this type of haptic communica-

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tion is the "Networked Vibrotactile Improvisation System" (NeVIS) developed by Hayes and Michalakos. NeVIS is a wired networked music performance system that exploits tactile feedback as a signaling tool between performers as well as between performers and laptops within an improvisational setting [4]. NeVIS system evaluation during live performances is evidence of the efficacy of haptic cues in performer-performer communication. However, NeVIS used wired technologies that has issues with performer's freedom of movement. MHWs were conceived to prevent issues due to wires by leveraging wireless connectivity [12]. Moreover, NeVIS was conceived and used for communication between only two performers, while MHWs were conceived to handle many performers linked via a wireless network.

Examples of MHW in the music technology industry are the tactile metronomes Pulse and BodyStrap by Soundbrenner[1] (which parallel research efforts in the academic community [3]). These wearables, which can be strapped to various parts of the body (wrist, chest, arm, leg), consist of a small wireless device equipped with a single vibration motor that delivers beat notifications via vibrotactile pulses. The beat delivered by the device haptically can be configured via a smartphone app and up to five devices can be synchronized to the same beat. However, Soundbrenner Pulse and BodyStrap only deliver the beat to the performers wearing them and do not support other types of wireless communication between performers.

In light of co-design findings we envision four types of network-based interactions enabled by MHWs for performers: between 1) co-performers, 2) performers and live sound engineers, 3) performers and Musical Things, and 4) performers and audience members. The object of this study concerns co-located interactions between performers, specifically electronic musicians, and audio engineers. The purpose of this research is to identify applications for MHWs that could go beyond those present in the literature conceived for similar musical purposes, as well as to design, develop, and evaluate MHWs. Finally, our research aims to assess the role of tactile stimuli in creative communication between performers, which to the best of our knowledge, has not been investigated in a systematic way. A video documenting the use of the MHWs co-designed in this study can be accessed at *www.iomut.eu*.

II. Participatory design methodology

Our methodology is based on participatory design [23] involving working with users and stakeholders from an early stage in the design process. This is motivated by the aims of better understanding the needs of contemporary electronic musicians playing in live settings and to let them shape how technology can benefit their culture and practice. Our approach was specifically inspired by applications of co-design in musical contexts reported in [24] and [25]. We adopted a structure composed of three consecutive stages:

1) an exploratory workshop with the goal to identify users' needs and communication issues during their musical practice;
2) an ideation workshop where participants explored the design of MHWs that could address some of the issues identified in the exploratory workshop;
3) a set of experiments where the designed MHW prototypes, implemented and refined by the authors, were evaluated by a group of users distinct from those who were involved in the designs.

[1] https://www.soundbrenner.com/

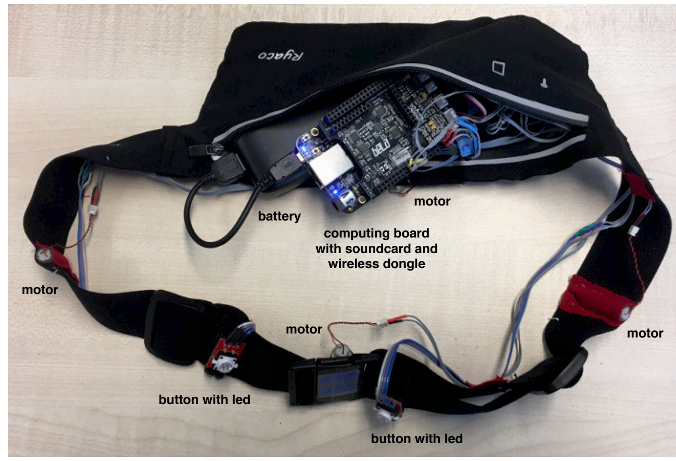


Fig. 1. Various components of the MHW prototype used in the technology demonstrations.

III. Exploratory workshop

A. Pilot prototype

We prepared a pilot prototype for the exploratory workshop to let participants experience an example of haptic wearable (see Figure 1). The system, previously presented in [12], is enclosed in a fanny pack fastened like a belt. The hardware components include a small fanny pack; the Bela board for low-latency audio processing [26], based on a Beaglebone Black board; a Wi-Fi USB dongle (NETGEAR A6100-100PES) for use as client, alternatively a small wireless router for use as server (TP-Link TL-WR902AC), the latter option features a USB port for 4G dongles enabling Internet connectivity (both solutions feature the IEEE 802.11ac standard); four vibration motors (Precision Microdrives 307-103) placed at the front, back, left and right of the belt of the fanny pack (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, respectively 28 ms and 49 ms); two push buttons with integrated led, placed at the front-left and front-right; a lightweight power supply (5V/2A). Following the recommendations reported in [27], to optimize the components of a Wi-Fi system for live performance scenarios to reduce latency and increase throughput, we configured the router in access point mode, disabled security, and limited it to support only IEEE 802.11ac. For software we wrote data processing and tactile stimuli synthesis programs using Pure Data programming language. Specifically, the Pulse Width Modulation technique was used for the tactile stimuli synthesis. Data reception and forwarding were achieved with OSC messages over User Datagram Protocol (UDP).

B. Participants

Ten male musicians aged between 23 and 37 (mean = 28.3, standard deviation = 4.9) participated in the initial workshop. This cohort had an average musical performance of 13.8 years. All were part of the laptop section of the "Orchestra Elettroacustica Officina Arti Soniche San Pietro a Majella". This orchestra is based in Naples (Italy) and its performers use both acoustic and electronic instruments. Of 50 musicians in the orchestra, 20 use laptops. In addition to strong backgrounds in electronic music, sound design, production, and sound engineering, all participants played conventional instruments or are singers. The workshop took place in a large room of the Conservatory of Music of Naples.

C. Procedure

1) Explanatory introduction: The exploratory workshop began with a presentation given by the experimenter, which introduced the concepts of the IoMusT [11] and the MHWs [12]. The purpose of the presentation was to provide effective understanding of the overall IoMusT framework and existing and planned technology, with a particular focus on MHWs.

2) Technology demonstrations: We then conducted technological demonstrations of two interoperable instances of the pilot prototype described in Section III-A. All participants were invited to wear the belt and were given examples of various tactile stimuli for about 5 minutes. These included vibrations with various types of dynamics and activation patterns of the four motors (specifically, circular patterns clockwise and counter-clockwise at two static and two varying speeds, one random activation patterns at two different activation speeds, simultaneous activations of either all motors or couples of motors with varying levels of amplitude and duty cycle). These patterns were selected such that the participants experienced a range including variations in space, time, and intensity.

In pairs, participants also tried the interoperability feature by using the push buttons. This allowed them to send control messages between each other, which were then interpreted and rendered by the receiving device as tactile stimuli. Furthermore, they could also experiment with smartphone and laptop apps to deliver wirelessly and simultaneously some control messages to the connected MHWs. Such demonstrations of the capabilities of the developed MHWs were organized to provide a basis for designing other solutions more specifically tailored to the needs identified in further focus group discussions.

3) Focus-group discussions: The discussions were structured to: i) establish an understanding of laptop orchestra practices; ii) understand technological constraints and issues of laptop orchestra; iii) establish an understanding of the limitations of current communication methods between performers of laptop orchestra and other actors interacting with them.

When a participant proposed a topic and a statement about it the experimenter asked all the other participants to comment whether they all agreed or not with such statement. This stimulated discussions where each participant exposed his own motivations or adjusted his vision thanks to the input of the others. For each topic, the experimenter asked participants whether they agreed or not with the concluding observations. Audio recordings of the focus groups were taken with a smart phone supported by further written notes taken throughout the discussion. The recordings were analyzed to identify the concluding observations with which the participants concurred.

D. Outcomes of focus-group discussions

We present below a set of observations on a range of topics with which the participants concurred after sharing and discussing their visions.

Visual communication. Especially in improvisation contexts, participants deemed that is often impractical or difficult to rely on visual communication of gestures to communicate. This stems from the fact that musicians' hands and/or feet are used to control a variety of interfaces (mouse, keyboard, controllers, foot pedals), and gaze is focused on the laptop screen, the display of a digital interface, or on peripheral interfaces. Participants stressed the fact that this is in particular true for large ensembles in the absence of a conductor when the performers are placed at distant positions in the venue, and in poor or low light conditions. Communicative gestures between performers during a performance on stage were considered inappropriate by participants as they are thought to be distracting from the performance and breaking the visual flow experienced by the audience. Moreover, electronic musicians often tend to isolate themselves from the rest of the ensemble, especially during an improvisation, so it is difficult to recall their attention (*"When playing we fully focus on our playing and on our instruments and it might happen that we forget about the others, even for several minutes"*).

Identification. The music produced by an ensemble of electronic musicians often becomes complex, and it may be difficult to decipher who is playing what or how a sound has been produced, especially when loudspeakers are not placed close to the instrument (*"Often we do not know nor understand who is playing and what is playing"*).

Communication with the conductor. Participants reported that when a conductor is present, there are often issues of communication between him/her and them since they must look at their screens or equipment in order to perform (*"We tend to not notice the conductor in time and sometimes we can loose his directions because we are focusing on the instruments"*).

Improvisation structuring. Participants pinpointed that in the absence of a conductor, they usually feel the need to devise strategies to organize the improvisations without visual gestures that disrupt the flow (*"Sometimes when we improvise in an ensemble, and especially with musicians with whom we never played, it is difficult to coordinate and we can get easily stuck on a section for several minutes while it would be great to change section/style"*).

Communication with the sound engineer. There is often a need to communicate to the sound engineers various information (e.g., notify them that a change in dynamic is going to happen soon, ask for eye contact to communicate a change of instrument during a piece, change some levels in the monitor loudspeakers or headphones). Often, the communication of such information needs to happen quickly in a live situation

(*"It is rather common to need to call the sound engineer's attention and it is frustrating when we can't make eye contact with him because he is focusing on something else, especially when we need to inform him quickly"*).

IV. Ideation workshop

A. Participants and procedure

A second four-hour workshop was held with the same participants to generate prototype ideas collaboratively the day after the first workshop. Using the bootlegging approach, that is, a *"structured brainstorming technique particularly suited to multidisciplinary settings"* [28], participants sketched MHWs that addressed some of the previously identified issues with current MHWs. The use of the bootlegging technique is *"to generate ideas in situations where the problem area or technology is fairly well defined but still open for new application ideas"* [28], the case for MHWs and the reason for using the methodology.

The theme of our bootlegging session was *"Applications of tactile stimuli during live performances of electronic music ensembles"*. Ideation categories were grouped into i) user topics: *types of users* and *type of musical activity/situation*, and ii) technical topics: *information types* and *information transmission methods* (e.g., with which transmitting/receiving devices, which haptic stimuli, number of motors, which sensors to use to transmit). During the idea generation stage, participants brainstormed for 10 minutes per category, producing post-its with dozens of variables for each of the four categories. Post-its were then randomly mixed to generate various combinations. Participants were divided into two groups of three and one group of four people. Each group was assigned to four combinations of variables. The groups then brainstormed potential applications by each of their variable combinations for 15 minutes. Finally, they selected the most interesting use case and prepared to present the concept with a mock-up design to be built with the available materials (see Section III-C2). After mock-up presentations from each group, the experimenter performed rapid prototyping of some of the proposed tactile stimuli to gather feedback and stimulate further discussion.

B. Outcomes of the bootlegging session

We present in this section the three mock-up designs generated by the groups. Each design included a taxonomy of tactile signals to be used to communicate a certain type of information. All ideas were refined together with the experimenter.

1) Chest-worn tactile system for performer-conductor communication: The first group presented a brooch-based MHW equipped with a single motor, to be attached in the upper chest area. The target users are performers of a 12-piece laptop orchestra. The scenario is a non-conventional conductor-laptop ensemble setting, where laptop performers are dispatched in the performance venue and the conductor is not facing directly the performers. Each laptop is associated with a loudspeaker placed nearby. The laptop orchestra is part of a symphonic orchestra, which is directed by a conductor. While the other performers are positioned on stage, the performers of the laptop orchestra are organized in four groups of three and positioned in different parts of the audience area (e.g., at the corners of the auditorium or on the balconies). Eye contact with the conductor who faces the stage is impractical. The conductor can deliver direction to the four sections of the laptop orchestra wirelessly using an app running on a tablet. The graphical user interface of the app displays four buttons and four sliders in a configuration on the screen that matches the physical position of the section in the space. The buttons are used to provide discrete cues (such as to start/stop playing, or to recall a performer's attention because a certain musical event is going to happen soon and he/she needed to prepare for it), while sliders are used to signal continuous cues (such as a change in the dynamics). To render the start/stop playing instruction a strong continuous vibration lasting 2 seconds is used, such that if performers are playing, they have to stop, and otherwise, they have to start. To recall a performer's attention a series of rapid intermittent pulses of medium intensity is provided over the course of 3 seconds. A series of intermittent pulses of increasing (or decreasing) intensity is provided within a time span of 5 seconds, to indicate an increase (or a decrease) of the volume of the sonic output of the section. The frequency of these pulses is lower than that of the pulses used for the "pay attention" cue to make these two cues more discernible.

2) Foot-worn tactile system for performer-sound engineer communication: The second group presented an application where the targeted users are members of an ensemble of four electronic musicians (without conductor) playing a composition in a concert hall and interacting with the sound engineer during the performance. The music produced by the ensemble, which is mixed live by the sound engineer, is delivered by a multichannel surround sound system placed around the audience. Each performer has a stage monitor. Performers can exchange information between them using tactile cues via the haptic belt described in Section III-C2. Thanks to the two buttons present on the belt they can deliver information to the sound engineer, who uses foot-worn MHWs. These foot-worn wearables include two motors placed on opposite sides of the ankle. Each motor is associated with a different musician according to their position in relation to the location of the sound engineer. Using the buttons the performers can communicate the following information to the sound engineer: 1) "Add delay plus reverberation to my sound": the input command is a single press of the left button which triggers rapid intermittent and strong vibrations lasting 6 seconds on the receiver side; 2) "Decrease my sound level in the monitor": the input command is a rapid succession of two presses on the left button which triggers a series of pulses of decreasing intensity lasting 5 seconds on the receiver side; 3) "Increase my sound level in the monitor": the input command is a rapid succession of two presses on the left button which triggers a series of pulses of decreasing intensity lasting 5 seconds on the receiver side; 4) "make eye contact with me" (to be able to convey other type of information using physical gestures): the input command is a single press of the left button which triggers a strong continuous vibration lasting 4 seconds.

3) Armband tactile system for co-performer communication: The third group presented an armband-based MHW involving two motors placed on each side of the arm. The users are members of an electronic music ensemble of four musicians without conductor, and the sound of each performer's instrument is amplified by a PA system. The envisioned scenario is a structured improvisation performed in an open-air concert venue. By structured improvisation participants meant a musical form consisting of a series of improvised sections with distinct character, which are predetermined by the composer or by the ensemble itself. Within each section, participants improvise freely within established constraints and expression. Specifically, participants envisioned a structured improvisation with four parts for each performer, where the parts are cyclically played in sequential order. The MHW is used to both send and receive information from performers. Besides the two motors, it is equipped with two buttons placed at two opposite positions (top and bottom) in order to be easily discernible and reachable by the hand from the side not wearing the device. The buttons are used to signal changes of sections to other performers by controlling only one of the two motors. The bottom button triggers intermittent vibrations of short duration in a 6-second timeframe to indicate that the change of section has to occur slowly. Conversely, the top button is mapped to intermittent vibrations of short duration in a 2-second timeframe to indicate that the change of section has to occur rapidly. By pressing one of the two buttons for a period longer than 2 seconds a performer instructs all the other performers to stop playing, so he/she can play a solo: if the bottom button is pressed the performers have to stop playing slowly, if the top button is pressed then they have to stop rapidly. These instructions are conveyed using both motors simultaneously involving continuous vibrations. The vibrations last a long time (6 seconds) for a slow fade out (bottom button), and are short (2 seconds) for a fast fade out (top button). To end a solo part, performers can press one of the two buttons triggering a change of section message on the receiver side. By pressing both buttons simultaneously a performer instructs all other performers to make eye contact with him/her. Such information is conveyed by slow intermittent pulses alternating between the two motors within a 5-second timeframe.

C. Tactile stimuli prototyping

After the mock-up presentations, the tactile stimuli envisioned in each mock-up were coded and presented back to participants. All participants in each group reported that the stimuli were effective in communicating their design ideas.

V. Implementation

Following the concept prototyping sessions, three tactile systems were implemented using hardware and software technologies similar to those used for the demonstration prototypes described in Section III-C2.

The chest-worn tactile system (see Fig. 2a) included a single motor contained within a custom-made piece of fabric. The fabric was taped to participants' chest using a hypoallergenic medical tape. A wire connected the motor to the Bela system, embedded in a belt fanny pack.

The foot-worn tactile system (see Fig. 2b) used four motors, also placed in custom-made pieces of fabric. Like for the chest-worn tactile system, the motors were connected to the Bela system through wires running along the body to reach the belt fanny pack. We chose small-sized motors to let participants insert them easily in their socks or shoes. After experimentation, it was decided to position the actuators inside participants' socks, on each side of the foot relatively to the central-bottom part above the sole (see the right side of Fig. 2b). This position was chosen instead of the originally envisioned ankle, not only to maximize sensitivity to the vibrations, but also to have a degree of sensitivity similar on both sides (we empirically found that compared to the central-bottom part above the sole, the ankles were less sensitive and led to a much less similar degree of sensitivity on both sides of the foot).

The armband tactile system (see Fig. 2c) included two motors contained in custom-made pieces of fabric sewed to the internal and opposite sides of an armband. Two buttons were attached to the front part of the armband which also contained the Bela system. A refractory period of 10 seconds was set to prevent the delivery of control messages if multiple performers were operating the buttons more or less at the same time.

A log system was created to ensure that all messages sent wirelessly were well received. We also created a virtual conductor program to send at various points in time some directions to performers equipped with the tactile wearables. Likewise we devised a virtual performer program to communicate time-based instructions to a live sound engineer having to modify the mix accordingly. Both programs were developed in the Pure Data environment. The control signals were sent wirelessly to the wearables using a laptop.

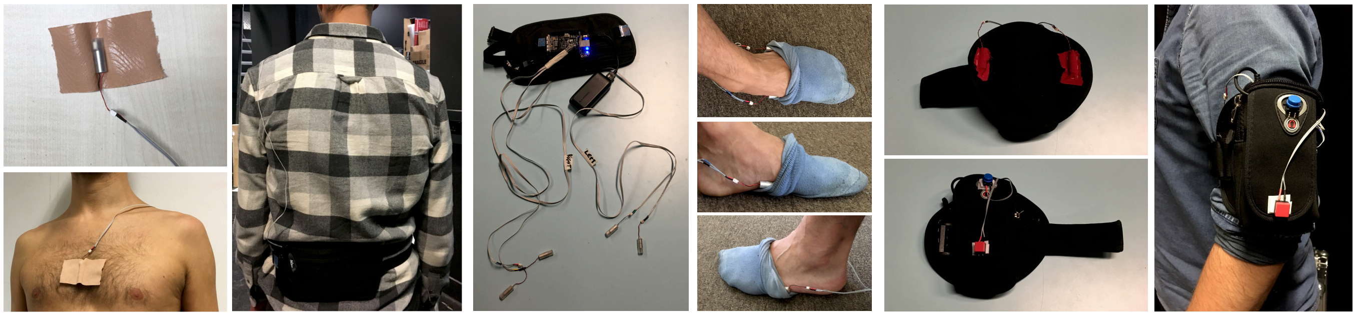
VI. Evaluation

All evaluation sessions were conducted in the Media and Arts Technology Performance laboratory at Queen Mary University of London, a purpose-built 80m^2 room in which concerts are regularly held. This provided an ecologically-valid setting for live electronic music rehearsal without an audience.

An Apple MacBook Pro 2016 laptop (with IEEE 802.11ac Wi-Fi standard) was used as a master computer to send tactile signals using the virtual conductor program described in Section V. The computer was also used to record participants responses. All MHWs were connected using a router (TP-Link TL-WR902AC). The experiments were filmed using an HD camera. Audio feedback was delivered using stage monitor loudspeakers placed in front of each performer.

In total twenty-five participants took part in the evaluations of the three systems. The evaluation participants were not involved in the co-design workshops in an effort to triangulate our findings with various sets of users. Pilot tests checked the equipment and procedures with a separate sample of evaluation participants.

In all evaluations participants were introduced to the procedure both orally and in writing before completing a consent



(a) Chest-worn tactile system. (b) Foot-worn tactile system. (c) Armband tactile system.

Fig. 2. The implemented Musical Haptic Wearables.

form. During the tasks, tactile stimuli were communicated in a randomized order across pieces of music and participants. The experimenter was seated at the center of the room, to start the virtual conductor/performer simulations and track eye contacts from participants over time when this was required by a task. The audio signals produced by the performers or sound engineers were recorded synchronously to the tactile signals sent to their devices.

Between each evaluation trial, performers had to complete a self-report questionnaire assessing agreement to topics presented in randomized order across participants. Measures of agreement were conducted using a visual analog scale (VAS) with 0 corresponding to "not at all" and 10 corresponding to "very much". At the end of the experiment participants were asked to fill in a post-task questionnaire also based on VASs. The post-task questionnaire also included several open-ended questions related to each tactile system.

In the different experiments, we measured the accuracy of the performers in responding to the tactile stimuli. This was defined as the percentage of correct actions following instructions communicated via the tactile system being assessed.

A. Evaluation of the chest-worn tactile system

1) Participants: Seven electronic musicians (1 female, 6 males) took part in the evaluation of the chest-worn tactile system. They were aged between 26 and 39 (mean = 32, SD = 4.8), with an average musical experience of 17.7 years. The participants were divided into one group of three and two groups of two performers, who had to perform live improvisations together.

2) Procedure: In each session, participants were invited to set-up the fanny pack and chest-worn system described in Section V with the help of the experimenter. Participants were invited to play collaborative improvisations using their digital music instruments of choice (three used a laptop and four used analog or digital synthesizers). To avoid potential visual communication between performers, they were positioned back to back in each corner of the room. During improvisations performers had to follow instructions communicated using the tactile stimuli described in Table I. The chest-worn tactile systems were wirelessly controlled by the virtual conductor program running on the master laptop.

The virtual conductor followed a series of "tactile scores" [29] composed by the first author. These were generated using aleatoric composition techniques [30]. Each composition lasted between 11 and 13 minutes, and involved the five stimuli. Each stimulus was repeated twice in a randomized order. All compositions started and ended with the "start" and "stop" direction respectively. The second "play" direction occurred after the first stop direction with no other stimuli in between. Stimuli were spaced by a random amount of time between 45 and 120 seconds (these durations were chosen to avoid too close presentations of stimuli that could disrupt the flow of the performance). The experiment included four compositions in total, therefore participants all experienced 40 stimuli trials (4 compositions $\times$ 5 stimuli $\times$ 2 repetitions). Before starting the task, participants were able to familiarize themselves with the system for 15 minutes during which each stimulus was presented 5 times.

Between each improvisation the participants answered the three questions Q1, Q2, and Q3 reported in Table II. The post-task questionnaire included the items Q4, Q5, and Q6.

3) Chest-worn tactile system results: The accuracy of the performers in response to the various tactile signals received via the chest-worn system is reported in Table I. On average participants reacted to the stimuli well, with a lowest percentage of about 70% for the stimulus asking them to pay attention to the conductor, and a highest percentage of 98% for the stimulus asking them to start playing. An in-depth analysis showed that most of the times the "pay attention" stimulus was confused with the "decrease volume" stimulus or not recognized at all, while "decrease volume" was sometimes confused with "stop playing".

Answers to VAS-based questions are reported in Table II. The quantitative results reported in Tables I and II are in line with the participants' written feedback. Four of them expressed the difficulty to discern "pay attention" and "decrease volume" and suggested that stronger vibrations (which could be provided by more than one motor) would have helped them to discern better those stimuli (e.g., *"I needed stronger vibrations to better understand which pattern was, somehow decrease volume got mixed with pay attention"*). Three participants also reported that the placement of the motor on the chest was not optimal due to a lack of sensitivity in this part of the body (e.g., *"Different motors in different places of the*

TABLE I
STIMULI AND RESULTS (MEAN±STANDARD ERROR) FOR THE CHEST-WORN TACTILE SYSTEM.

Conductor's direction	Type of tactile signal	Expected action (at the end of the tactile signal)	% Correct responses
Start playing	Continuous vibration of strong intensity lasting 2 seconds	Start playing	98.21±1.78
Stop playing	Continuous vibration of strong intensity lasting 2 seconds	Stop playing	94.64±2.52
Pay attention to the conductor	Series of rapid intermittent pulses of constant and medium intensity in the span of 3 seconds	Turn towards the center of the room to make eye contact with the experimenter. You can continue playing while doing so	69.64±7.14
Increase volume	Series of intermittent pulses of increasing intensity and duration in the span of 5 seconds	Increase instantly your volume after receiving this signal. You can stay at the louder volume for a duration of your choice	96.42±2.3
Decrease volume	Series of intermittent pulses of decreasing intensity and duration in the span of 5 seconds	Decrease instantly your volume after receiving this signal. You can stay at the quieter volume for a duration of your choice	82.14±5.35

TABLE II
VAS-BASED QUESTIONS AND RESULTS (MEAN±STANDARD ERROR) FOR THE CHEST-WORN TACTILE SYSTEM.

ID	Question	Results
Q1	Effectiveness	6.5±0.3
Q2	Discernibility	6.12±0.41
Q3	Ability to follow instructions	6.78±0.38
Q4	Clarity of "start/stop playing" direction	8.6±0.45
Q5	Clarity of "pay attention" direction	6.5±0.61
Q6	Clarity of "dynamics change" direction	5.65±0.93

body would make the wearable easier to use"). Moreover, three participants reported to have missed the identification of some stimuli because due to a high level of involvement while playing (e.g., *"I think I missed some commands because I was in the flow"*).

B. Foot-worn tactile system evaluation

1) Participants: Six male live sound engineers evaluated the foot-worn tactile system. They were aged between 24 and 31 (mean = 28.1, SD = 2.9), with an average musical experience of 14.7 years, and an average experience as live sound engineers of 7.2 years.

2) Procedure: In each trial, one sound engineer was invited to put on the foot-worn system described in Section V. Participants used a mixing desk as in an actual live performance and reacted to four tactile stimuli during pre-composed pieces, as described in Table III. The wearable was controlled by four virtual performers simulated with our Pure Data patch. The virtual performers were physically represented by numbered panels positioned in different locations of the room. The experimenter tracked if and when the sound engineer pointed towards specific virtual performer when requested by a tactile instruction.

Four pieces each lasting 9 minutes were composed using audio material recorded during the evaluation of the chest-worn tactile system. Each piece comprised four parts (one for each virtual performer) and included 16 tactile stimuli in total (four stimuli per virtual performer). Each instruction was repeated four times during the task. Stimuli were spaced by a random period between 20 and 40 seconds (such durations were chosen to simulate a live music performance where musicians would need to communicate often with the sound engineer). Participants underwent a total 64 trials. Before starting the task they familiarized themselves with the system for 15 minutes, during which each stimulus was provided 4 times.

Between each piece to be mixed, the sound engineers answered the questions Q1 to Q4 reported in Table IV. The post-task questionnaire included the items Q5 to Q8.

3) Foot-worn tactile system results: Accuracies in responses of sound engineers to tactile stimuli can be found in Table III. On average participants reacted to stimuli almost perfectly (accuracies around 98%). Statistics on answers to VAS-based questions are reported in Table IV.

In line with the quantitative results, most of participants reported that it was easy for them to decipher the tactile stimuli and which virtual performer they were associated with (e.g., *"Vibrations are easy to decode and do not interfere with already busy senses/channels of communication"*). Four of them were also very positive about using MHWs which would significantly help their communication with performers in real live music shows, especially when visibility is reduced (e.g., *"This kind of wearables can help me dealing with poor lighting and fog effects created by smoke machines"*). Moreover, two participants reported that tactile stimuli could be a good complement to information communicated through gestures (e.g., *"The system can be a good support to visual communication"*).

C. Evaluation of the armband tactile system

1) Participants: Twelve electronic musicians (all males) took part in the evaluation of the armband tactile system. They were aged between 20 and 68 (mean = 32.7, SD = 13.2), with an average musical experience of 18.8 years. The participants were divided in three groups of four performers who had to improvise together.

2) Procedure: The participants were invited to wear the armband tactile system described in Section V on their non-dominant arm. Performers could use electronic instruments of their own (six used a laptop in conjunction with various kinds of controllers and five used analog and/or digital synthesizers, one used DJ equipment). As in the experiment described in Section VI-A, performers were positioned in the corners of the room back to back to avoid line of sight. Each participant

TABLE III
STIMULI AND RESULTS (MEAN±STANDARD ERROR) FOR THE FOOT-WORN TACTILE SYSTEM.

Performer's instruction	Type of tactile signal	Expected action (at the end of the tactile signal)	% Correct responses
Make eye contact	Continuous vibration of strong intensity lasting 4 seconds	Point with the hand towards the virtual performer who gave the instruction	100±0
Apply effect	Series of rapid intermittent pulses of constant and medium intensity in the span of 6 seconds	Increase for few seconds the fader of the effects corresponding to the virtual performer who gave the instruction	98.95±1.04
Increase volume	Series of intermittent pulses of increasing intensity and duration in the span of 5 seconds	Increase for few seconds the fader of the volume corresponding to the virtual performer who gave the instruction	98.95±1.04
Decrease volume	Series of intermittent pulses of decreasing intensity and duration in the span of 5 seconds	Decrease for few seconds the fader of the volume corresponding to the virtual performer who gave the instruction	95.83±3.09

TABLE IV
VAS-BASED QUESTIONS AND RESULTS (MEAN±STANDARD ERROR) FOR THE FOOT-WORN TACTILE SYSTEM.

ID	Question	Results
Q1	Effectiveness	7.39±0.4
Q2	Task discernibility	7.15±0.41
Q3	Performer discernibility	7.79±0.34
Q4	Ability to follow instructions	7.6±0.37
Q5	Clarity of "make eye contact" instruction	8.6±0.24
Q6	Clarity of "apply effect" instruction	7.35±0.35
Q7	Clarity of "increase volume" instruction	6.94±0.52
Q8	Clarity of "decrease volume" instruction	6.65±0.5

was assigned two roles (conductor and/or performer) during the sessions. When acting as conductors, participants had to direct the others by sending instructions using the buttons of the tactile device. When acting as performers, participants had to react to the tactile stimuli received from the conductor. The various conductor and performers' interactions with the tactile system are summarized in Table V. Conductors also acted as performer during the session but were free to play whatever they wished. They experienced the same vibrations of the performers to have a confirmatory feedback of the instructions they sent. When acting as conductors, participants could see a list of directions they had to follow from a laptop. They could annotate on a GUI which direction they sent to performers to ensure they covered each of the five directions twice during a trial. Conductors were instructed to leave at least 30 seconds between instructions not to break the flow of the performance. Before starting the sessions participants familiarized with the system for 20 minutes during which each tactile stimulus was presented at least 4 times. Each participant also acted as a conductor using the buttons.

This task was conceived to measure if conductors managed to learn and correctly apply a set of pre-conceived directions. The experimenter monitored the conductor's directions using a Pure Data application running on the master laptop. The application counted OSC messages associated to each direction. When directions were not repeated twice the monitoring application reported the information to the experimenter who would then deliver the corresponding message using the virtual conductor application (this was to ensure that a similar number of instructions were sent in each session).

In each session performers experienced each tactile stimulus at least twice, the whole experiment was a total of 30 trials (5 tactile stimulus $\times$ 6 times). To avoid potential biases due to responses of other participants to the stimuli, participants were told they would not always receive the same instructions. On average each session lasted 13.5 minutes. After each session participants answered questionnaires matching the role they had. Tables VI and VII show the questions for conductors and performers respectively.

3) Armband tactile system results: Statistics on conductor and performer accuracies are summarized in Table V. Participants correctly reacted to the stimuli on overall, with a lowest accuracy of about 96% for conductors and 91% for performers.

Statistics on answers to VAS-based questions are reported in Tables VI and VII for conductors and performers respectively.

Five participants pointed out that the armband tactile system was not obtrusive, but that they would have preferred a lighter and smaller device, like a bracelet (e.g., *"I would improve the device making it much smaller, perhaps it is better if it went on the wrist"*). Three of them also advised to use devices that could be worn in multiple parts of the body to increase the number of possible information to communicate and to better differentiate the stimuli (e.g., *"I think that the device could be on several parts of the body so to have more signals and make them more separated and more obvious"*). Three participants reported the need for more creative control when covering the role of conductor, in order to be able to give a wider range of directions, such as tempo changes, tempo and dynamics changes, or the possibility of communicating with only one specific performer or a subset of performers (e.g., *"The system was effective in communicating the instructions but there is very little creative control, it is not possible to communicate more specific changes in the performance."*, *"I did enjoy using it, but felt limited by only having two choices for each button."*). Moreover, two participants reported to have ignored or not recognized some of the stimuli during the experiment because they were immersed in the flow of performing (e.g., *"It's a good way to send and receive orders without giving much attention, but information can be lost or ignored when too focused on playing"*).

4) Comparison between the systems: A binomial logistic regression was performed using indicator contrasts with two different systems as reference to ascertain the effects of the system type on the likelihood that participants reacted correctly to the haptic stimuli. The logistic regression model was statistically significant ($\chi^2(2) = 30$, $p < 0.001$), indicating

TABLE V
STIMULI AND RESULTS (MEAN±STANDARD ERROR) FOR THE ARMBAND TACTILE SYSTEM USED IN CONDUCTOR AND PERFORMER ROLES.

Conductor's action	Conductor's direction	Type of tactile signal	Expected performer's action (at the end of the tactile signal)	% Correct responses
Press for more than 2 seconds the top blue button	Change section slowly	Intermittent vibrations of short duration in the timeframe of 6 seconds	Radically change your style and sounds, involving a very smooth change	Conductor: 95.83±4.16 Performer: 95.83±2.99
Click the top blue button	Change section rapidly	Intermittent vibrations of short duration in the timeframe of 2 seconds	Radically change your style and sounds, involving a very fast change	Conductor: 95.83±4.16 Performer: 93.05±3.81
Press for more than 2 seconds the bottom red button	Stop playing with long fade out	Continuous vibration in the timespan of 6 seconds	Stop playing decreasing slowly the volume in order to create a long fade out of at least 10 seconds. Then start playing after about 15 seconds	Conductor: 95.83±4.16 Performer: 94.44±3.13
Click the bottom red button	Stop playing with short fade out	Continuous vibration in the timespan of 2 seconds	Stop playing decreasing rapidly the volume in order to create a fast fade out. Then start playing after about 15 seconds	Conductor: 100±0 Performer: 93.05±3.21
Click both buttons simultaneously	Make eye contact	Slow intermittent pulses alternating between the two motors within a timeframe of 5 seconds	Make eye contact with the conductor	Conductor: 100±0 Performer: 91.66±3.24

TABLE VI
VAS-BASED QUESTIONS AND RESULTS (MEAN±STANDARD ERROR) FOR THE ARMBAND TACTILE SYSTEM USED AS CONDUCTOR.

ID	Question	Results
Q1	Ability to control	8.55±0.38
Q2	Ease of use	6.73±0.72
Q3	Ability to communicate "make eye contact"	7.61±0.52
Q4	Ability to communicate "stop playing with long fade out"	7.42±0.53
Q5	Ability to communicate "stop playing with short fade out"	7.63±0.51
Q6	Ability to communicate "change section with long fade out"	7.55±0.53
Q7	Ability to communicate "change section with short fade out"	7.73±0.52

TABLE VII
VAS-BASED QUESTIONS AND RESULTS (MEAN±STANDARD ERROR) FOR THE ARMBAND TACTILE SYSTEM USED AS PERFORMER.

ID	Question	Results
Q8	Effectiveness	7.54±0.33
Q9	Discernibility	7.17±0.3
Q10	Clarity of 'make eye contact" instruction	8.27±0.28
Q11	Clarity of "stop playing with long fade out" instruction	7.98±0.29
Q12	Clarity of "stop playing with short fade out" instruction	7.58±0.34
Q13	Clarity of "change section with long fade out" instruction	7.28±0.35
Q14	Clarity of "change section with short fade out" instruction	7.08±0.38

an overall effect of the system type. Regarding the pairwise comparisons between the systems, results showed that participants' accuracy was significantly lower for the chest-worn tactile system compared to both the foot-worn tactile system (Odds Ratio = $exp(\beta)$ = -8.41; 95%, CI = [-22.57, -3.72]; $p < 0.001$) and the armband tactile system (Odds Ratio = $exp(\beta)$ = -3.56; 95%, CI = [-7.15, -1.88]; $p < 0.001$).

VII. DISCUSSION

The co-design process presented in this paper attempted to address issues associated with creative communication between performers of electronic music ensembles and their collaborators (conductor, sound engineer). Some of the issues and needs reported by participants in the initial workshop were in line with previous works. For instance, the problem of visual communication between electronic music performers during performance was in line with the concerns reported by different authors (see e.g., [15], [4]). The issue of delivering information from the conductor to performers in conditions of scarce visibility, in large scale performances, or in distributed performances was also raised by Armitage and Ng [31]. The performers' need of identifying how a sound has been produced during a performance, which is related to the knowledge of the internal state of a digital musical instrument, was also highlighted by Michailidis and Berweck [32]. In general, the focus discussions revealed that there is a need for devices capable of delivering information that does not tamper with the visual channel, and the use of MHWs was regarded by participants as a promising avenue. The bootlegging session achieved the aim of stimulating creativity in participants and opening up a range of possibilities for creative communication that go beyond conventional solutions.

We implemented and evaluated in ecologically-valid conditions three wearables conceptualized during the co-design sessions. Very high accuracies to tactile stimuli were obtained for the foot-worn tactile system where participants reacted almost perfectly to all tactile stimuli. This finding parallels results from other studies on tactile recognition tasks involving the feet [33]. Along the same lines, the armband tactile system led to very high accuracies. The chest-worn tactile system obtained a lower accuracy overall albeit still high. Participants reacted significantly better to three out five stimuli and it was identified that issues related to chest sensitivity (see e.g., [34], [35]) and clarity of the signals. Notably, participants indicated the need for stronger vibrations, which could be improved using, for instance, two motors.

The armband tactile system was the only MHW designed with inputs to send messages in addition to motors. The interaction with the controls was found to be well-designed, and the actions were described as intuitive and easy to remember.

Nevertheless, from the participants' comments the need for a wider range of directions emerged. Some participants reported to find extremely useful to have controls directly from a wearable device, but that touch-screens would likely allow one to diversify the pool of possible directions.

All participants agreed that tactile stimuli could be an effective alternative to most common forms of communications such as gestures or screen-based notifications. A recurring comment was however that tactile stimuli could be even more useful if integrated with visual feedback to recall the receiver's attention to what is displayed on phones' or tablets' screens. In all experiments participants envisioned tactile signals and information that could be conveyed other than those which were proposed. Furthermore, six participants desired the functionality to program the device and customize it via an app. Interestingly, seven participants reported the same issues and needs related to visual communication and improvisation structuring, which were described by participants of the co-design phase (see Section III-D).

As with every new tool with a certain level of complexity and novel affordances, MHWs require some training to learn the different stimuli and associated actions. A recurring comment, common to all experiments, was that a more extensive training and continuous practice would have led to better performances. The results reported here involved a training duration of only a few minutes as opposed to a consolidated practice so it is anticipated that a longer practice time would achieve greater accuracies in performer responses.

Taken together these results provide evidence that tactile stimuli can be an effective medium of communication for members of electronic music ensembles, their conductor, and the live sound engineer. These findings concur with Hayes and Michalakos when using the NeVIS system, where the two designers-performers reported that tactile communication helped them to improve general communication on stage [4]. However, the present study also has limitations. Firstly, it is possible that some of the observations reported during the co-design sessions relate to the practice of the specific ensemble the participants are part of, and that members of other ensembles may recount different experiences. Moreover, despite the evaluation sessions being conducted in ecologically-valid conditions for a performance rehearsal, tests performed during real concerts with an audience would better assess the potential and limits of MHWs. Having an audience present may indeed affect performers' responses. We plan to conduct this investigation in future work. In addition, in the two experiments that involved playing, five participants reported that sometimes the tactile information could be lost or ignored when in the flow of the performance. Another comment reported by three participants in all experiments was that whole body vibrations generated by low frequencies at high amplitudes provided by sub-woofer in real concerts, might interfere with the tactile signals delivered by a MHW. Therefore, care should be taken to design tactile stimuli that could be discernible also in presence of other conflicting vibrations.

Only male participants took part in the co-design sessions due to the unavailability of female participants within the study period. This has some likely implications on the designs resulting from the participatory process. The designs and in particular the proposed body positions for the wearables may not all be gender inclusive as they may better suit males than females. This is especially the case for the chest-worn MHW. Feedback collected from one female participant highlighted that the chest was not a convenient location for a MHW. Our next co-design sessions will include females to ensure that the devised artefacts are gender inclusive.

Another limitation of the study comes from the relatively small numbers of participants in the participatory design and evaluation studies. This leads to several possible caveats: i) the participatory design sample may not be representative of the population of electronic music performers, conductors and live sound engineers, implying that other designs may have emerged with different groups, ii) the participants who took part in the evaluations may not be representative of the population of performers preventing the generalization of the results on the accuracy of the different tested systems.

Finally, it is worth noting that MHWs, and the results reported here may be used to support musical communication for visually-impaired performers through haptic interfaces (see e.g., [36]). To date, this line of research has been scarcely addressed despite its potential to greatly benefit blind performers.

VIII. Conclusion and future work

This paper investigated the design, implementation and evaluation of "Musical Haptic Wearables for performers", a novel class of wearable devices conceived to enhance creative communication between performers and their collaborators. We first conducted a workshop engaging ten performers in focus-group discussions to understand the communication needs of electronic musicians in a live performance context. We then conducted a second workshop with the same participants to sketch MHWs and applications, taking into account the emerging themes. We assessed the co-designed wearables with a distinct group of electronic musicians. Our results indicate that there is interest for tactile communication based on wireless systems, and that such a communication might be a substitute or an improvement for more conventional forms of communication based on gestures or screen notifications.

In this work we focused on electronic musicians. In the future we will repeat the present experiment involving different types of musicians and assess their needs in light of the findings found for electronic musicians. We also plan to design new MHWs and to validate them in real live music concerts. Furthermore, we will extend the results of this study for the application of MHWs for performer-performer interactions in remote settings. Other types of interactions will also be addressed such as between performers and Musical Things [11], as well as between performers and audience members (see e.g., [37]), in co-located or remote settings.

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