Listening to Your Brain: Implicit Interaction in Collaborative Music Performances

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ABSTRACT

The use of physiological signals in Human Computer Interaction (HCI) is becoming popular and widespread, mostly due to sensors miniaturization and advances in real-time processing. However, most of the studies that use physiology-based interaction focus on single-user paradigms, and its usage in collaborative scenarios is still in its beginning. In this paper we explore how interactive sonification of brain and heart signals, and its representation through physical objects (*physiopucks*) in a tabletop interface may enhance motivational and controlling aspects of music collaboration.

A multimodal system is presented, based on an electrophysiology sensor system and the Reactable, a musical tabletop interface. Performance and motivation variables were assessed in an experiment involving a test "Physio" group (N=22) and a control "Placebo" group (N=10). Pairs of participants used two methods for sound creation: implicit interaction through physiological signals, and explicit interaction by means of gestural manipulation. The results showed that pairs in the Physio Group declared less difficulty, higher confidence and more symmetric control than the Placebo Group, where no real-time sonification was provided as subjects were using pre-recorded physiological signal being unaware of it. These results support the feasibility of introducing physiology-based interaction in multimodal interfaces for collaborative music generation.

Keywords

Music, Tabletops, Physiopucks, Physiological Computing, BCI, HCI, Collaboration, CSCW, Multimodal Interfaces.

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1. INTRODUCTION

In recent years, physiology-based systems have led to implicit models of interaction where the user's physiological signals, such as brain waves, electro-dermal activity (EDA) or heart rate, are monitored, mapped and transformed in commands to control devices and applications [23]. This interaction paradigm is based on internal states of the human body and has been explored by different disciplines such as cognitive psychology, neuroscience, physiological computing, enactive media and HCI. However, most of these studies are focused on single-user scenarios, either in clinical rehabilitation [27], or in communication and control applications [4]. At the same time, the use of electro-physiological systems in collaborative scenarios and Computer-Supported Collaborative Work (CSCW) is still scarce.

In this paper we present a collaborative music system that combines implicit interaction based on physiology sensing and explicit interaction based on a tangible interface for real-time sound generation and control (Reactable) [13]. This multimodal system displays physiological signals through sound, graphics and physical objects (*physiopucks*) which can be manipulated by physiology emitters and their partners. We hypothesize that such use of physiological signals via (*physiopucks*) will enhance motivational and controlling aspects of music creation in collaborative scenarios.

The study of HCI systems based on the combination of physiological signals and tabletops has not been widely explored. We are only aware of two similar studies using physiological signals and tabletops [28] [9], which nonetheless lack the collaborative and musical aspects that this paper aims to analyze in order to contribute to the understanding of such a paradigm.

To assess the effect of physiology-based interaction in music collaboration using the aforementioned system, task-oriented experiments between pairs of participants were carried on. Performance and motivational aspects of music collaboration were assessed using self-report methods.

2. STATE OF THE ART

2.1 Physiology-based Music

In the process of designing a physiology-based interface, specific body states are mapped to an explicit display technique [1]. For example, this can be achieved through interactive sonification, which allows the exploration of physiological signals by their adaptive transformation into sound [10].

Research on sound and music computing pioneered the use of bioelectrical signals in interactive systems. Rosenboom's implementations of physiological measures for music generation are among the first outstanding works in the field. His musical systems presented parameters and textures driven by electroencephalography (EEG) and heart rate, among other physiological techniques [25].

More recent research associates EEG-acquired data with musical imagination [20], leading to new techniques and devices, such as Miranda's Brain-Computer Music Interface (BCMI) *Piano System* that trains the computer to identify EEG patterns associated with cognitive musical tasks, or generative systems for music mixing [21]. Finally, neurofeedback training systems have been developed in the effort to enhance music and creative performance [8].

2.2 Electro-physiology Sensor Systems

Conventional electro-physiology systems use electrical conductors to measure electrical signal derived from brain and body activity. For instance, Brain Computer Interfaces (BCI) use electrodes placed in the scalp to measure brain electrical activity (EEG) and transform it into commands that allow control of devices and applications [23]. Therefore, it provides a non-muscular communication channel that has been widely used in clinical rehabilitation. Physiological interfaces may also include the measurement of other biopotentials different to brainwaves, such as electrocardiography (ECG) or electrooculography (EOG), using a single device.

2.3 Musical Tabletop Interfaces

There has been a proliferation of musical tabletops in the past decade. Projects such as the Audiopad [22], the MusicTable [2] or the Reactable [13], started showing the possibilities and affordances of tangible tabletop musical instruments. Some of these devices are more oriented towards sound synthesis (e.g. Reactable), some towards composition (e.g. Xenakis [3]) or sequencing (e.g. Scrapple [18]). Some are meant for professional or experienced musicians, while others are more oriented towards education or entertainment (e.g. Zen Waves [7]).

Independently of the many differences that can exist between all these systems, scholars tend to agree in the benefits resulting from interacting with these large-scale tangible and multi-touch devices. Their vast screens make them excellent candidates for collaborative interaction and shared control [6], while supporting real-time, multidimensional as well as explorative interaction. These characteristics also make tabletops especially suited for both novice and expert users. Additionally, we think that the visual feedback possibilities of this type of interfaces, makes them ideal for understanding and monitoring complex mechanisms, such as the several simultaneous processes that can take place in a digital system for music performance [13].

3. SYSTEM ARCHITECTURE

In this paper we present a first working prototype of a multimodal system for collaborative sound generation and control, combining physiological computing and a tabletop interface[1]. This section describes the extraction and processing of the physiological signal, the mappings applied for physiology-based sonification, its parameters for sound generation and control, finishing with the integration with the Reactable framework.

[1]Video available on `http://www.vimeo.com/14675468`

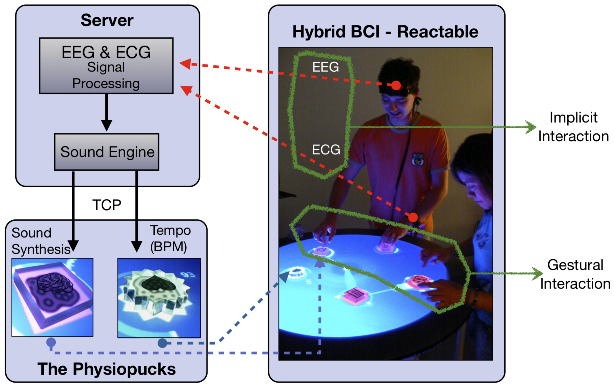

Figure 1: Multimodal Music System. Physiological signals (red dotted arrows) are wirelessly streamed to a server that applies a signal processing and sonification. EEG-based sound synthesis and tempo control through heart rate are integrated in the Reactable framework, and presented to performers as physiopucks (blue dotted arrows).

3.1 Signal Extraction and Processing

The proposed system uses Starlab's *Enobio* for physiological signal extraction. *Enobio* is a wearable, wireless electrophysiology sensor system that captures three biopotentials: EEG, ECG and EOG. It features 4 channels connected to dry active electrodes with a sample rate of 250hz, a resolution of 0.589μv, maximum Signal-to-Noise Ratio of 83db, a 16-bit Successive-Approximation Register (SAR) Analog-to-Digital Converter, and an automatic offset compensation for each channel [26].

Figure 1 describes the system's design. A dry electrode is placed on the frontal midline (Fz) lobe of participants for EEG recording [16]. The electrode for heart rate detection is placed in the wrist of subjects using a wristband. Physiological signals are acquired, amplified and streamed wirelessly to a server application for processing and sonification. There, the synchronization is managed by the Enobio software suite, that applies a digital filter to reduce noise (centered between 50 and 60hz) and sends the EEG and heart rate data to the sound engine. At this stage, a EEG-based sound synthesis and a tempo control based on heart rate are computed and streamed to the Reactable framework via a TCP/IP port.

3.2 Sound Engine

In this study, the selection of physiology sonification methods had two motivations. First, we wanted to provide feedback with minimal delay about changes from different frequency bands of EEG. Second, we aimed at easily recognizable sonification that would stand out from other sounds generated using a musical tabletop interface.

The system's sound engine uses a direct mapping between EEG alpha-theta bands (4-12Hz) and the audible sound frequency spectrum. This mapping was motivated by alpha-band neurofeedback designs [8]. This EEG processing unit appears as a sound generator puck (brain-labeled *physiopuck*) on the Reactable. On the other hand, the heart rate is mapped to another puck to control tempo or beats per minute (BPM) on the Reactable (heart-labeled *physiopuck*) (see Figure 1).

The Pure Data (Pd) computer music system [24] performs the real-time signal analysis and sound synthesis. It has been chosen due to its openness and suitability for performing such tasks, and for its flexibility when defining the mappings. This software also favors a robust integration with the Reactable framework, whose sound engine has been built with Pd.

3.2.1 EEG and Heart Rate Signal Processing

The computed magnitude spectrum for each EEG frame is used to shape the spectrum of a white noise signal. Each frequency bin is then used to weight the first 128 frequency bins of a 256 bins white noise FFT. Working at 44.1 kHz for audio synthesis, a frequency range going from 0 Hz to 11025 Hz is covered, with each frequency bin taking about 86 Hz. The spectral magnitudes are equalized by weighting the chosen curve to emphasize the weaker higher frequencies. The sound resynthesis stage consists of an overlap-add of the inverse FFT of the weighted and equalized magnitude spectrum of each consecutive processed EEG signal block and is entirely handled by the Pd synthesis engine. The resynthesized audio signal is finally streamed over a TCP-IP/LAN connection to a server running the Reactable software, where the EEG-based sound synthesis and the heart rate tempo control are finally mapped to the *physiopucks*.

The heart rate signal is processed by first applying an adaptive rescaling of the system. A two-seconds sliding window (500 samples) checks for the minimum and maximum values. Therefore, the signal is normalized depending on that range. This adaptive approach compensates for the signal without losing heart rate peak resolution. Peaks in the heart rate are detected by applying a simple threshold function. A heartbeat is detected if the normalized signal is above the 40% of the normalized range. A new heartbeat is then detected only if this signal falls below 30%.

3.3 Integration into the Reactable

The Reactable's sound synthesis and control methods follow a modular approach, a prevalent model in electronic music, which is based on the interconnection of sound generators and sound processors units. In the Reactable this is achieved by relating pucks on the surface of the table, where each puck has a dedicated function for the generation, modification or control of sound. Reactable's objects can be categorized into several functional groups such as audio generators, audio filters, controllers (which provide additional control variables to any other object) or global objects (which affect the behavior of all objects within their area of influence) [13]. Each of these families is associated with a different puck shape and can have many different members, each with a distinct and human-readable symbol on the surface. Because of this modular approach, the integration of a physiological subsystem into the standard Reactable was straighforward. Two new pucks (*physiopucks*) were created, allowing the performers to use their physiological signals to generate and control sound, in the same manner as using standard Reactable objects (see Figure 1).

4. EXPERIMENT

To assess the effect of physiology-based interaction on collaborative music experiences, and to evaluate the performance of the proposed multimodal system, we designed a task-oriented experiment of music creation involving two participants. Each experiment took around 45 minutes and was designed to measure *performance* and *motivation* using self-reported ratings. The experiment was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

4.1 Experimental Setup and Task design

The experiment involved a pair of participants with two distinct roles: one termed *user* who operated the Reactable pucks with her hands, and one termed *emitter* who manipulated the standard pucks but also provided the physiological signals for the *physiopucks*.

These *user-emitter* pairs worked with a set of six standard Reactable pucks plus the two *physiopucks*. After a first explorative phase, two five-minute tasks were to be completed. Each task consisted in replicating 15-seconds prerecorded music excerpt created with the same pucks that were available to the participants during the test. All *user-emitter* pairs listened to the same music reference. Once the excerpt was played, the *user-emitter* pair had up to 5 minutes to mimic the sound. The participants were able to replay the reference at any time by asking the experiment leader. This task-oriented design was applied to encourage the *user-emitter* pair in a music composition process.

During the task, the *user* manipulated the pucks in the surface of the Reactable (gestural interaction) whereas the *emitter* performed both gesturally and through her own physiological signals mapped to the *physiopucks* (implicit interaction). *Physiopucks* were available for both *emitters* and *users* to be combined with any of the standard Reactable objects.

4.2 Sample and Groups

A total of 32 participants, age mean of 28.09 years old (SD=3.5), 15 females and 17 males, with no experience using the Reactable, took part in the experiment. They were distributed in two groups: a Physio Group (N = 22) where signals from the *emitter* were mapped in real-time to the *physiopucks*; and a Placebo Group (control group, N = 10) where *physiopucks* were driven by pre-recorded EEG and heart rate signals, thus providing no real feedback to the *user-emitter* pairs. Participants were unaware of this effect and *emitters* in both groups were told they were controlling the *physiopucks*. The physiological signals used by the Placebo Group were recorded from a person who composed the reference music excerpt and were similar to the ones in Physio Group.

4.3 Measures

Measures were taken using three self-reported tools: (1) Pre-test questionnaire: demographics, general music knowledge, electronic music skills and Reactable knowledge; (2) Post-test questionnaire with 10 measures representing motivation and performance, based on a 5-points Likert scale ranging from "strongly agre" to "strongly disagree", except where noted or implied; (3) Self-Assessment Manikin (SAM) using 9-points pictorial scale for emotional valence and arousal [17].

Each measure in the post-test questionnaire contained from 2 to 5 questions. The measures concerning collaborative performance were based on [12] and involve Feedback (M1), Distribution of Control (M2), Social Affinity (M3) and Nature of the Task (M4). The motivation measures were based on [11], which describes Curiousity (M5), Difficulty (M6), Confidence (M7) (10-points Likert scale), Control of the Interface (M8), Motivation (M9) and Satisfaction (M10). The detailed description of these factors and questionnaires can be found in [19].

5. RESULTS & DISCUSSION

The ratings from the abovementioned questionnaires were collected and analyzed for 4 types of participants: physio-emitters (subjects manipulating pucks and providing physiological signals for the *physiopucks*); physio-users (subjects manipulating pucks and interacting with physio-emitters); placebo-emitters (subjects manipulating pucks, believing they were providing physiological signals for the *physiopucks* when those were actually pre-recorded); and placebo-users (subjects manipulating pucks and interacting with placebo-emitters). The data was collected through computer-based questionnaires, and mean was taken over the questions corresponding to each measure.

Two analyses were done. First, t-tests were applied to compare the means between participants within each experimental group (subsection 5.1) and between them (subsection 5.2). Second, the variation of all responses within each tested pair (emitter and user) was evaluated by applying a Pearson correlation analysis (subsection 5.3). No significant differences were found for the demographic data collected in the pre-test questionnaires.

5.1 Emitters vs. Users Analysis

In these analyses, we compared the differences between emitters and users within each experimental group.

5.1.1 Physio Group: Emitters vs. Users

In this analysis only *Motivation* ratings (M9) was close to significant, $t(21) = -1.90, p = .071$, with physio-emitters being more motivated than physio-users. Both types of participants reached similar levels of *Difficulty* (M6), and the *Distribution of Control* (M2) did not show significant difference between physio-emitters and physio-users (see Figure 2, left quadrants).

The lack of significant difference for all measures could be an indicator that both *emitters* and *users* within the Physio Group had a similar experience during collaboration. Importantly, these factors differed from Placebo Group, as shown in the next subsection.

5.1.2 Placebo Group: Emitters vs. Users

The analysis showed two results. *Difficulty* ratings (M6) was significant, $t(9) = -3.57, p < .01$, with placebo-emitters declaring higher challenge ($M = 2.46, SD = 0.18$) than placebo-users ($M = 1.93, SD = 0.27$) (see Figure 2, right quadrants). This may show that placebo-emitters could perceive that the feedback was not working properly. Secondly, the analysis unveiled significant differences for *Distribution of Control* (M2) ($t(9) = -2.35, p < .05$) as shown in Figure 2. Placebo Group showed an asymmetric tendency, with placebo-emitters declaring higher Control ($M = 2.80, SD = 0.44$) than placebo-users ($M = 1.80, SD = 0.83$).

A high perception of *Difficulty* from the placebo-emitters would potentially force them to take a more active role in "making system work", forcing placebo-users to give up a more active role in the control distribution.

5.2 Between Group Analyses

In these analyses, we compared ratings of emitters and users from different experimental groups.

5.2.1 Physio-Users vs. Placebo-Users

Physio-users declared higher *Confidence* (M7) ($M = 5.06$, $SD = 1.45$) in the task as compared to placebo-users ($M = 3.55, SD = 1.19$), $t(15) = 2.03, p < .05$. Importantly, while the settings were identical for *users* in both groups, the confidence of placebo-users could be affected by the lack of clear feedback perceived by placebo-emitters. In a similar manner, the difference in *Distribution of Control* (M2) was significant between users in both groups, $t(15) = 2.6, p < .05$. Operating under the same conditions, physio-users reported

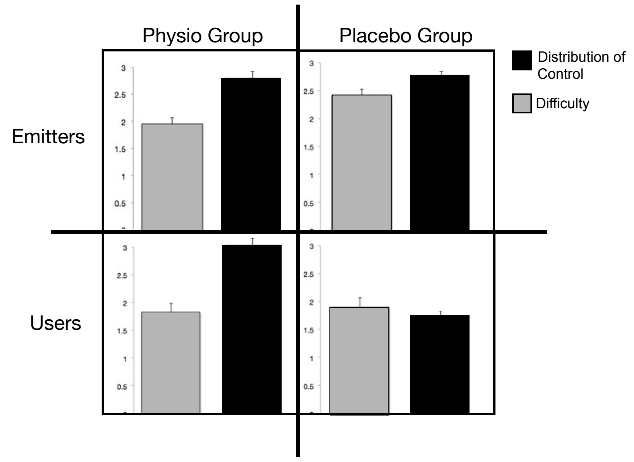

Figure 2: Ratings for *Difficulty* (M6) and *Distribution of Control* (M2) measures in four participant types (scale from 0 to 5). Error bars show standard deviation. See sections 5.1 and 5.2 for the details.

higher *Control* ($M = 3.00, SD = 0.89$) than placebo-users ($M = 1.80, SD = 0.83$). Figure 2 (lower quadrants) clearly shows this effect. As mentioned in section 5.1.1, physio-users did not show an asymmetric *Distribution of Control* compared to their physio-emitters. However, this measure is significantly lower for placebo-users compared to placebo-emitters.

5.2.2 Physio-Emitters vs. Placebo-Emitters

Physio-emitters showed higher *Confidence* levels (M7), ($M = 4.90, SD = 1.06$) compared to placebo-emitters ($M = 3.65, SD = 0.96$) at $t(15) = 2.24, p < .05$. Second, placebo-emitters reported greater *Difficulty* (M6)($M = 2.46; SD = 0.18$) than physio-emitters ($M = 1.96, SD = 0.64$) $t(15) = -2.37, p < .05$. The introduction of a sham pre-recorded signal for placebo-emitter had a clear effect not only in the performance and motivation of these participants, but also in the role of their partners (i.e. placebo-users).

5.3 Correlation analysis

To study in depth the synchronization between *user* and *emitter* in participant's pair, we applied a correlation analysis to evaluate the consistency between their responses to each questions. When all measures were combined together, both Physio and Placebo groups show high level of response consistency between user-emitter pairs. Interestingly, when correlations were analyzed measure by measure, a different picture emerged (see Table 1).

The *Feedback* measure (M1) showed higher correlation for Physio pairs ($r = 0.51$) than for Placebo pairs ($r = 0.25$). In the case of the former, the correlation level shows the importance that both participants assigned to the audiovisual feedback coming from the system during the collaborative tasks. Placebo pairs responses are almost uncorrelated, which indicates that placebo-emitters were not able to recognize the feedback coming from the Reactable, and such a factor also affected placebo-users collaborating with them.

The correlation analysis of *Collaborative nature of the tasks* (M4) showed differences between Physio and Placebo user-emitter pairs. Whereas the Physio pairs showed moderate and significant correlation between participants (i.e. there was an agreement on considering the tasks as collaborative), the Placebo pairs' ratings were not correlated. This

Table 1: Pearson correlation coefficients of *user-emitter* pairs responses for Physio and Placebo Groups (*significance at 0.05, **at 0.01, ***at 0.005 level)

Measures	Physio	Placebo
All measures	0.80***	0.68***
Feedback (M1)	0.51**	0.25
Distribution of Control (M2)	0.51	0.53
Social Affinity (M3)	0.52**	0.64
Nature of Task (M4)	0.41**	0.21
Curiousity (M5)	0.49***	0.63*
Difficulty (M6)	0.43*	0.72*
Confidence (M7)	0.81***	0.51***
Control of the Interface (M8)	0.11	0.42
Motivation (M9)	0.34	0.03
Satisfaction (M10)	0.62***	0.62**
Arousal	0.25	0.6
Valence	0.13	-0.17

result supports the feasibility of physiology-based interaction for music collaboration.

For *Difficulty* measure (M6), ratings from user-emitter pairs were highly correlated in Placebo but not for Physio group (see Figure 1). Interestingly, valence-arousal ratings were not highly correlated except arousal ratings for Placebo group, which corroborates the results for difficulty measure.

Measure of *Control of the Interface* (M8) showed moderate correlation for Placebo, but not for Physio Group. Together with a significant asymmetry between emitters and users in the Placebo Group when running the t-test, this shows that this asymmetry was consistent among its *user-emitter* pairs.

Finally, *Motivation* measure (M9) were almost uncorrelated between *user-emitter* pairs in both groups. This is especially interesting for the Placebo Group, as it shows a tendency to lose interest in the performance during collaboration.

6. GENERAL DISCUSSION

The presented results highlight specific aspects of a system that combines implicit, physiology-based and explicit, tabletop-based interaction in music collaboration. Similar levels of rated difficulty and strong correlation of confidence ratings for user-emitter pairs in Physiology group show that this new multimodal system do not impose major difficulties for music collaboration. On the contrary, the similar ratings of distribution of control - a fundamental factor for assessing the symmetry of music collaboration - that were given by the Physio Group (but not Placebo) show that the proposed implicit interaction model encouraged symmetric music collaboration between the participants.

The results also show that placebo-emitters expressed higher levels of difficulty and lower levels of confidence. While such experiences were expected for participants who where provided with a fake biofeedback, it is notable how these affected the experience of their partners, placebo-users. As an example, we can mention the significantly lower level of confidence in placebo-users as compared to physio-users, regardless them both operating the system in the same conditions. This reciprocity effect in the performance of participants has to be taken into account in the design of multimodal interfaces for music collaboration.

The experiment also helps to understand the perceptual aspects of display techniques based on physiological signals. The scores corresponding to audiovisual feedback reached a high correlation in the Physio Group, but not in the Placebo Group. This indicates that the participants were able to perceive whether the feedback from the sonification engine and the Reactable graphical interface was linked to their physiological signals or not. This factor is particularly interesting for collaborative music performances, as it shows that a direct mapping between EEG spectral bands and the audible sound frequency spectrum is effective as an identifiable auditory display. It also unveils that both *emitters* and *users* were able to recognize the sound processes driven by physiological signals, within a multimodal musical interface that included other control paradigms (e.g. gestural input). However, the musical expressivity arising from such design has to be further explored, as discussed in the next section.

6.1 Future Work

Several potential upgrades for the system are foreseen. First, alternative EEG sensing devices can be used in order to improve signal acquisition and cover other regions of the brain. Second, regardless the fact that subjects did not perceive significant latency when running the experiment, a better communication protocol can be applied to improve the connectivity between modules and reduce latency, for instance by using Open Sound Control (OSC). Finally, other sonification mappings can be applied in order to achieve higher musical expressiveness and intuitiveness. Designs based on adaptive systems can be envisioned, where physiological signals are monitored only covertly, in absence of user's intentional control. Such collaborative system could then passively monitor performers' perceptual, cognitive and emotional states and use real-time machine learning methods for adaptive multisensory feedback. [5] [15] [14].

Future experiments can be complemented with time measures (e.g., how long does it take to complete a task using the system), physiological measures (recording of EEG, ECG and EDA) that characterize psychophysiological states, visual recording for behavioral observation (gestures, facial expressions), qualitative data from the participants and similarity metrics between the sound references and recorded trials. Importantly, future studies will involve pairs of *emitters* performing together, instead of a *user-emitter* design. This will allow to study physiological synchronization between performers. Finally, to assess the musical possibilities of the multimodal system, experiments with professional musicians can be carried on, given their previous training.

7. CONCLUSIONS

Physiological computing in collaborative HCI applications is a rapidly developing field of research that require new experimental paradigms and methodologies. This paper presents a multimodal system for music collaboration, and a methodology for assessing participants' performance and motivation. The analysis has shown that the combination of implicit, physiology-based and explicit, tangible interaction is (a) feasible for participants collaborating in music composition, and (b) that it preserves a balanced distribution of control between collaborators. These results strongly support the use of physiological interfaces for music collaboration, as they can lead to meaningful and novel experiences in the field of CSCW and music creation. Together with the creation and control of sounds, brain and body signals may be powerful indicators of performer's emotional and cognitive states during collaboration, guiding music anticipation and interpersonal synchronization.

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