SONIFICATION OF BRAIN AND BODY SIGNALS IN COLLABORATIVE TASKS USING A TABLETOP MUSICAL INTERFACE

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ABSTRACT

Physiological Computing has been applied in different disciplines, and is becoming popular and widespread in Human-Computer Interaction, due to device miniaturization and improvements in real-time processing. However, most of the studies on physiology-based interfaces focus on single-user systems, while their use in Computer-Supported Collaborative Work (CSCW) is still emerging. The present work explores how sonification of human brain and body signals can enhance user experience in collaborative music composition. For this task, a novel multimodal interactive system is built using a musical tabletop interface (Reactable) and a hybrid Brain-Computer Interface (BCI). The described system allows performers to generate and control sounds using their own or their fellow team member's physiology. Recently, we assessed this physiology-based collaboration system in a pilot experiment. Discussion on the results and future work on new sonifications will be accompanied by practical demonstration during the conference.

1. INTRODUCTION

The measure of human brain and body states has been explored by different disciplines, namely cognitive psychology [1], neuroscience [2] and physiological computing [3]. In Human Computer Interaction (HCI) the use of physiology-based devices is becoming increasingly popular and widespread, mostly due to sensor miniaturization and real-time processing [4]. This allows the transformation of the users' physiological signals, such as brain rhythmic activity, electro-dermal activity (EDA) or heart rate, in commands for controlling devices or computer applications [5]. However, most of these studies focus on single-user setups, while physiological signals usage in Computer-Supported Collaborative Work (CSCW) and other collaborative scenarios is still just an emerging field.

In the present work we demonstrate the benefits of physiological computing for multimodal collaborative interaction. In order to include physiological cues into a Computer-Supported Collaborative System, we chose sonification of brain and body signals as a display technique. Sonification permits data exploration by transforming it into sound [6]. Over several decades Electroencephalographic (EEG) data have been successfully sonified in a number of application domains: for biofeedback and real-time monitoring systems [7], in exploratory data analysis [8], for enabling communication with Locked-in Syndrome patient [9], online inspection of clinical data [10], or live music performance [11] [12].

One can classify the applications that rely on EEG sonification according to two dimensions: musicality of the output and whether

Table 1: Sonifications for physiological signals. Application domains resulting from musical and non-musical display techniques, and their usage for revealing physiology and for biofeedback purposes.

	Musical Sonification	**Non-musical Sonification**
Revealing Physiology to others	*Performance, Collaboration, Communication*	Medical diagnosis
Biofeedback (self-monitoring)	Relaxation	Alert systems

the signals are meant to be heard solely by a user, or by other people (see Table 1). Our work addresses the upper left quadrant of Table 1. Indeed, sonification has a strong potential for expressing user implicit physiological states in real-time, especially, in collaborative tasks. First, auditory system is better suited for perception and analysis of complex dynamic patterns. Second, audition allows for tracing multiple auditory streams withing a mixture of sounds.

We hypothesize that using sonification of physiological signals via tangible objects (*physiopucks*) will enhance motivational and controlling aspects of music collaboration. To explore such a paradigm, we developed a multimodal interactive system shaped by a tabletop interface (collaborative environment) for music generation (collaborative activity), where the performer's brain and body signals are used to generate and control sounds.

Aiming to explore the auditory display of brain and body signals in HCI, we present a first prototype of a collaborative music system that combines two paradigms of interaction:

- Implicit interaction through physiological sensing
- Explicit interaction based on a tabletop interface for sound generation and control (Reactable)[13].

This design allows sound operations mainly dependent on physiology-based sonification and hand gestures, as sonifications are represented by physical objects (*physiopucks*) that give direct access to the performers' own body signals and those originated by their partners.

We have chosen a tabletop for our system since scholars tend to agree on its benefits for collaborative interaction and shared control [14], while favoring at the same time, real-time, multidimensional as well as explorative interaction. Additionally, the visual feedback possibilities of this type of interfaces, makes it ideal for

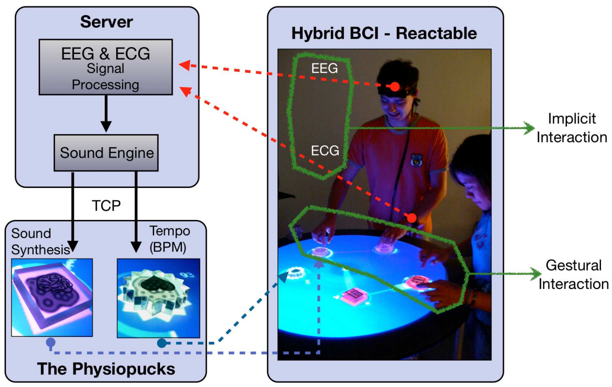

Figure 1: Multimodal Music System. Physiological signals (red dotted arrows) are wirelessly streamed to a server that applies a signal processing and sonification. EEG-based sound synthesis and tempo control through heart rate are integrated in the Reactable framework, and presented to performers as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

understanding and monitoring complex mechanisms, such as the several simultaneous processes that can take place in a digital system [15]. Finally, we focus on music collaboration since it represents one of the densest forms of human communication [16].

The study of HCI systems based on the combination of physiological sonification and tabletops has not been widely explored. We are only aware of one study using Brain-Computer Interfaces (BCI) and tabletops [17], which nonetheless lacks the collaborative and musical aspects that our system aims to include. In the field of EEG sonification, Hermann et al. have developed a tangible computing system in order to interactively control real-time and offline data sonifications [18]. This work is mostly centered on exploratory analysis of multivariate data, as is the case of EEG, and thus does not explore the affordances of physiology-based sonification when applied to a collaborative music environment. However, this work addressed interesting aspects for our system, such as shared control and multi-user setups.

2. THE BCI-REACTABLE SYSTEM

2.1. Hardware

Fig. 1 describes the system architecture. For physiological signal extraction, it uses Starlab's Enobio [19], a wearable, wireless, hybrid BCI device that captures three biopotentials: EEG, Electrocardiogram (ECG) and Electrooculogram (EOG). It features 4 channels connected to dry active electrodes with a sample rate of 250hz, a resolution of 0.589v, 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 [19].

The tabletop system for music collaboration has been built using the Reactable framework [13]. The Reactable is an electronic musical instrument that uses a tabletop tangible interface, which allows the performers to control the system by manipulating tangible objects (pucks) and with their fingers. The instrument is based on a luminous round table, and by putting pucks on its surface, by turning them and connecting them to each other, performers can combine different elements like synthesizers, effects, sample loops or control elements in order to create a composition [20]. The Reactable hardware is based on an acrylic surface (35.4 inches of diameter) for rear projection. A camera situated beneath the table, continuously analyzes the surface using the reacTIVision tracking system [21] for the recognition of player's fingertips and the nature, position and orientation of physical objects that are distributed on its surface. A projector, also from underneath the table, draws dynamic graphics on its surface, providing a visual feedback of the state, the activity and the main characteristics of the sounds produced by the audio synthesizer.

Regarding auditory display, two loudspeakers are located at both sides of the Reactable to enable stereo sonification.

2.2. Physiological Signal Extraction and Processing

A dry electrode is placed on the frontal midline lobe (Fz) of participants for EEG recording, according to the 10-20 International System [22]. The electrode for heart rate detection is placed in the wrist of performers using a wristband. Physiological signals are acquired, amplified and streamed wirelessly via IEEE802.15.4 to a server application for data processing. The BCI synchronization is managed entirely by the Enobio software suite that applies a digital filter to reduce noise (centered between 50 and 60Hz) and send the EEG and heart rate data to the sound engine.

The aforementioned design permits out-of-the-lab performances, as real-time EEG and heart rate signals are acquired without the need of skin preparation or electrolytic gel, commonly used for the extraction of low amplitude physiological signals. Hence, the regular procedures of electrode preparation, placement and stabilization are significantly reduced in time.

2.3. Sonification Approaches

The sound engine creates a direct mapping between EEG spectral bands and the audible sound frequency spectrum. This EEG analysis and resynthesis 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 Fig. 1).

The Pure Data (Pd) computer music system [23] 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 mappings. This software also favors a robust integration with the Reactable framework, whose sound engine has been built with Pd. A sound file containing an excerpt of the EEG audification is available in [24]. The sample also displays a sequence based on a piano sample to show the changes in tempo patterns produced by the ECG-tempo *physiopuck*.

2.3.1. Audification of EEG signals

The system applies a single-stream audification of EEG measures (see Fig. 2). As pointed out by Hermann et al. [18] audification is the most direct sonification technique and stands out as a good choice to inspect time series data. Therefore, 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 44.1kHz for audio synthesis, a frequency range going from 0Hz to 11025Hz is covered, with each frequency bin taking about

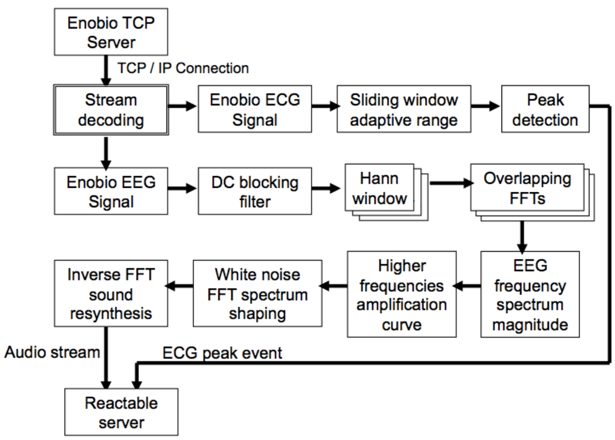

Figure 2: Physiology-based sound engine, block diagram. Signal processing for EEG sonification and ECG tempo control.

86Hz. 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 is finally mapped to the *physiopucks*.

2.3.2. *Tempo control using ECG signals*

ECG measures are used as a control mechanism to adjust the BPM of the system to the averaged heart rate of the user (see Fig. 2). ECG signal is processed by first applying an adaptive rescaling. 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 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% (see Fig. 3).

2.4. 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 generator and sound processor 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 objects can therefore be categorized into several functional groups such as audio generators, audio filters, controllers or global objects [16]. Each of these families is associated with a different puck shape and can have many different members, each with a distinct (human-readable) symbol in the surface.

Because of this modular paradigm, the integration of a physiological subsystem into the standard Reactable was straightforward.

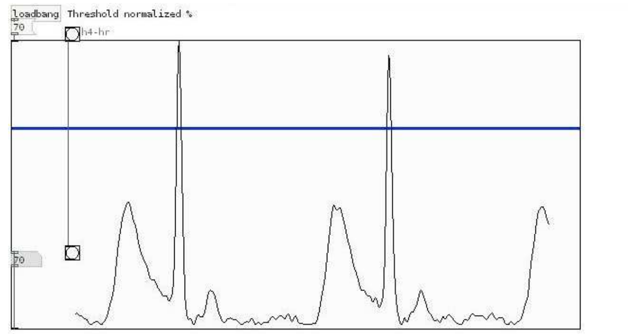

Figure 3: Threshold function for ECG peak detection in Pure Data. An adaptive rescaling compensates preserving peak resolution. A heartbeat is detected when the signal is above the 40% of the range. A new heart beat is detected only if the signal falls below 30% of the range.

Type	Subtype	Connection	quantity	Shape
Generator	EEG resynthesis	1 audio out N control in	1	
Global	ECG Tempo	N control out	1	

Figure 4: Description of *Physiopucks*: The EEG-based sonification (upper line) is classified as a Generator within the Reactable framework (subtype "EEG resynthesis") It has assigned one stereo output and *n* control inputs, allowing combination with any standard Reactable filter and controllers. The ECG-Tempo controller (lower line) belongs to the family Global objets, hence affecting the BPM of all ongoing operations in the Reactable when it is placed in the surface of the tabletop interface.

A brain-labeled *physiopucks* allow the direct display of EEG sonification by putting it on the surface of the Reactable. The system also permits to change its amplitude by moving a graphical slider projected on the right side of the *physiopuck* (see Fig. 4). A heart-labeled *physiopuck* adjusts the global tempo of the system to ECG measures by placing it on top of the Reactable. Also, a graphic pulse coming from the center of the table and a numeric display placed on the top-right corner of the *physiopuck* work as indicators of the current BPM rate (see Fig. 4). The system returns to 125 BPM (pre-defined standard tempo) when the *physiopuck* is removed from the surface.

Through this interaction design performers can use their physiological signals to generate and control sound, and combine it with standard Reactable objects such as filters and controllers.

3. A PILOT STUDY

To assess the effect of physiology-based sonification in collaborative music experiences, and to evaluate the performance of the

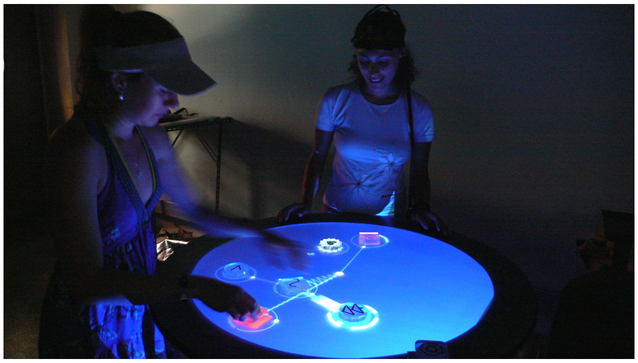

Figure 5: Two participants performing in a collaborative musical task using the multimodal system. The emitter (center) wears a hybrid BCI device that streams EEG and ECG signals wirelessly to the system for sonification. The user (left) combines standard pucks (in blue) and *physiopucks* (in violet and white) for generating sound compositions.

proposed system, we designed a task-oriented experiment for collaborative music composition with 32 users. The experiments were conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. For more details about the experimental design and its results see [25] and [26].

The study involved pairs of participants with specific roles: one user (explicit interaction), that operated the Reactable with his or her hands; and one emitter (implicit interaction) that manipulated the standard pucks but also provided the physiological signals for the EEG sonification and ECG-BPM control (see Fig. 5).

For this initial experiment, subjective measures were assessed using a post-test questionnaire based on a 5-point Likert Scale. It included 10 different factors concerning motivation and collaborative performance such as *Challenge*, *Confidence* and *Leadership*.

The study revealed four main effects of physiology-based sonification applied to a collaborative music performance. First, the levels of reported *Challenge* for both types of participants (emitters and users) were similar and did not reach a significance difference. Second, the introduction of a physiology-based feature to the Reactable did not affect the *Confidence* levels of the collaborative performance. On the other hand, Control Group, were emitters worked with prerecorded EEG and ECG signal being unaware of it, not only reached lower *Confidence* ratings, describing the system as less responsive and controllable, but also showed higher levels of *Challenge* and a loss of *Curiosity* in a correlation analysis, revealing a lack of will to perform with others.

The significances detected in this measures lead us to confirm that emitters were able to perceive whether the audiovisual feedback was linked to their physiological signals or not.

4. FUTURE WORK DIRECTIONS

Based on our initial studies, we have identified a number of research directions which have implications for new sonifications that we can use for the refined system.

- Implicit interaction for collaboration: in our system the physiological signals allow the addition of implicit cues by means of visualization and/or sonification techniques. We will continue investigation on how these may enhance collaborative experiences and how it may affect communication and shared control between the users.
- Expressiveness and Intuitiveness: our system aims to foster expressivity in real-time performance. At the same time, the applied sonification mappings account for a rapid recognition of real-time biofeedback information. We will further investigate what level of mapping complexity will be optimal to sonify and/or visualize continuously changing physiological states.
- Multisensory biofeedback: our system provides both visual and sound feedback. Future studies will search for optimal spatio-temporal parameters of multisensory feedback conveying several physiological signals from multiple users.

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